Cornel Stan

Future Fire Forms

Heat, Work and Thermodynamics

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Preface

Keep on running by clever burning!

Many people want to replace firepower with electricity from photovoltaics and wind power. Is this a good strategy? Can solar panels and wind turbines solely ensure all the world's primary energy?

Fire has shaped the existence of Homo sapiens for millions of years: as the only living being on the planet, it needs fire for the preparation of its food. He has always needed fire to make bricks, cement and steel. He has used fire to build machines that work for him or move his being on land, at sea and in the air. Above all, he always utilized fire for his warmth at home and when working.

In a first part of this book, over five chapters, there is described how man created materials, machines, heating systems and power plants with the help of fire. It is shown how the fire in some heat engines directly acts on the working fluid and in others indirectly, via heat transfer to the working fluid.

Neither combustion nor thermal engines are responsible for the environmental hazard till now, but the fossil fuels they have received so far. Let's feed the fire with climate compatible fuels: In this context, resources, potentials and properties of environmentally friendly or completely climate-neutral fuels such as hydrogen, biogas, ethanol, methanol, vegetable oils and synthetic fuels are presented. The emissions that a fire can cause, from carbon dioxide to nitrogen oxides and to particulate matter, are also set out.

In a second part of the book, which consists of six chapters, it is shown which rules of the game must be respected when developing efficient and at the same time environmentally friendly machines with a heart of fire for the future. This second part treats the essential laws of technical thermodynamics, the exchange possibilities between heat and work, of the efficiency of a conversion of one form of energy into the other, underlining the fact that the energy cannot increase due a conversion. Ways are shown on which the heat can be converted into work, during processes in thermal machines. Furthermore, the three ways of transferring heat, conduction, convection and radiation, are explained and supported with examples. In all this thermodynamic world, two rules have to be followed: the irreversibility of the processes in nature and technology, as well as the phenomenological approach, which also should be a guide for everyone in the own live.

In a third and final part of the book, which consists of three chapters, it is explained whether and how to tame a fire. At first, this seems hardly possible, because fires using fossil fuels are still a very, very profitable business for their promoters, exporters and intermediaries.

Nevertheless, new, climate-friendly fuels allow the fire to unfold properly in very economically operating machines and systems! Automobiles with a heart of fire and electric wheels are just as much a part of this as gigantic ship engines with methanol and diesel engines with hydrogen. But also, a fire based on garbage, manure and plant residues, or a second-hand heat have a considerable potential for the future!

How heat and work can be generated alternatively, without fire, is shown in a final section: Wind power, hydropower and photovoltaics are analyzed and discussed in a compact form with regard to their physical mode of action, technical designs and worldwide use. It becomes clear that these forms cannot be enough to secure all the primary energy of the world.

The last weapon, nuclear power, is presented and discussed as well.

What would man be without fire?

This book is an attempt to convince specialists, but also every reader not to give up such an irreplaceable energy source as the fire.

Cornel Stan Zwickau, Germany, June 2022

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Part I

Combustion in the modern world

1

The fire

1.1 Prometheus' burning gift to humanity

The sun, which radiates light and warmth to our earth, never glided somehow over the heads of the people from Beijing to Washington in the past. At that time, there was neither Beijing nor Washington.

In the imagination of our ancestors, the sun walked across the sky in a chariot pulled by four stallions.

Re was the fire god in Egypt, having the responsibility for warmth and light.

Agni was in Hindu mythology "god of fire", a main god of Hinduism.

Köjin was the fire goddess in Japanese mythology.

Alaz was the fire god in Turkish mythology.

Sethlans was the fire god of blacksmiths and crafts among the Etruscans.

In Sicily, *Adranus* watched over Etna, the volcano that always spits fire.

In Mesopotamia, according to sources from Sumeria, the fire god was *Gibil*.

And finally, in Hawaii, *Pele* was not a football god, but the goddess of fire, winds and volcanoes.

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In the Greek mythology the driver of the sun chariot in the sky was the sun god *Helios* himself. In the morning *Eos* opened the way for him, in the evening *Selene* followed him. Mythology granted later, beginning with the fifth century BC, this honorable task to God *Apollo,* who until then had many other obligations:

Fig. 1.1 Apollo and the Sun Chariot, Georg Friedrich Kersting, 1822

God of light, healing, spring and the arts, especially music and poetry.

But the sun in the sky was also the source of the sacred fire, whose guardian *was Hestia (Vesta* for the Romans), the goddess of home and hearth. Hestia, sister of the supreme Olympian god of Greek mythology, *Zeus* (in the Romans *Jupiter*), was the eldest daughter of *Kronos*.

And Kronos, for his part, was the youngest son of Earth *(Gaia)* and Heaven *(Uranus)* [4].

So the granddaughter of Earth and Heaven guarded the Olympic Fire. Her nephew, *Hephaestus (Vulcan by* the Romans), son of Zeus, was in charge of the use of fire, as the god of blacksmithing and architecture: he created not only the palaces of all the gods, but also the lightning and thunderbolt of Zeus, and even Helios' sun chariot!

But the gods wanted the fire only for themselves, for the further constructions, the warming and the nutrition of their prosperous society. The legend poets of antiquity were obviously true visionaries, they probably sensed the development of our modern world.

Fortunately, there were also fire bringers, then as now. In the case of the ancient Greeks, it was Prometheus (the "forward-thinking"), a brother of the head of the gods Zeus. When the earth was created but had no intelligent inhabitants, he took clay and created humans. He taught them, in addition to reading, writing and arithmetic, to build houses and create art. And one day he captured for his dear, freezing people the fire that arose from some sparks of the Helios-Sun Chariot (Fig. 1.1).

The gods didn't like that at all. Zeus had the thief chained to a rock by the fire application god Hephaestus. To the people who were so happy about the fire, Zeus sent a charming fairy named Pandora, with a can, as a gift. However, this box should not be opened under any circumstances. But people have always done what they are forbidden to do, even the old gods knew that exactly. From the box escaped, as the price of fire, all troubles and vices - evil, toil, disease and even death. And so the Bad conquered the world. In the box, however, despite the hasty return, hope remained.

Some authors believe that the box was opened again later. And still other authors do not share this view, but they now hope that this will happen at some point.

1.2 Fire radiates its energy like the sun

The sun has temperatures on its surface between 5500 – 6000 degrees Celsius (°C). (*in the interior of the sun* there are *temperatures of up to 15 million °C*). As a comparison: the temperature of a healthy person on his surface, i.e. on the skin, is 36°C.

In principle, every kind of body emits electromagnetic **waves** due to its temperature [1]. This is referred to as energy radiation, but generally as heat **radiation** (due to the wave frequency in the infrared range, on which the maximum energy content is sent).

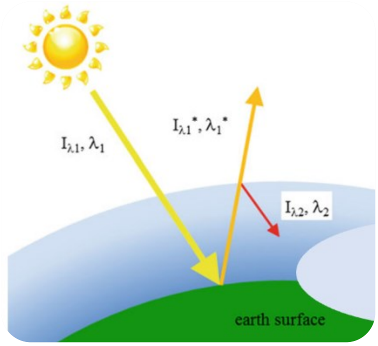
Heat transfer by radiation basically takes place without body or mass contact, by means of very tiny, oscillating particles called **photons.**

So the sun radiates energy towards people. But man, also radiates energy towards the sun! However, the balance is determined by the sun, due to the much greater **radiation intensity** *(energy flux per volume unit)* on a much higher frequency of electromagnetic waves *(oscillations per second, referred to as Hertz).*

A radiation is basically distributed on all wavelengths, but their intensity has a temperature-dependent maximum and decreases very abruptly on the neighboring wavelengths, as shown in (Fig. 1.2) (bottom plot).

The highest intensity of solar radiation is given in the wavelength range of visible light.

The integration of all the wavelength-dependent radiation intensities results in the heat flux density (Eq.1.1). The heat flow supplied by the radiation results from the multiplication of the heat flux density by the irradiated surface (Eq.1.2). The effect of the heat flow over a certain period of time (Eq.1.3) is the supplied energy in form of heat.



$$\dot{q} = \int_{-\infty}^{+\infty} I_\lambda(\lambda) \cdot d\lambda \qquad (1.1)$$

$$\dot{Q} = \dot{q} \cdot A \qquad (1.2)$$

$$Q = \dot{Q} \cdot t \qquad (1.3)$$

I_λ	$\left[\frac{W}{m^2} \cdot \frac{1}{\mu m}; \frac{W}{m^3}\right]$	energy flux per volume unit (radiation intensity)
λ	$[\mu m\ ;\ m]$	wave length
$\dot{q}$	$\left[\frac{W}{m^2}\right]$	energy flux density (heat flux density)
$\dot{Q}$	$[W]$	energy flux (heat flux, heat flow)
Q	$[Ws\ ; kWh\ ; kJ\ ; kcal]$	energy (heat)
t	$[s\ ; h]$	exposure time
A	$[m^2]$	surface

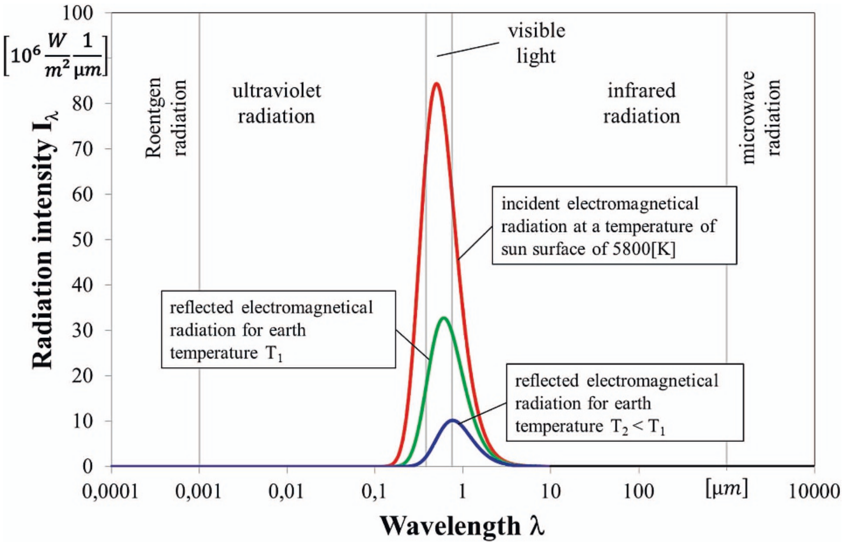


Fig. 1.2 Intensity and wavelength of sun radiation

As mentioned earlier, solar radiation is emitted for the most part in the frequency range of thermal radiation [2]. Within this range, by the way, is also the radiation visible to humans, or simply, the light **radiation.**

It is precisely in this visible range that solar radiation has its highest intensity, even if low proportions are emitted at lower frequencies *(infrared range)* or at higher frequencies (*ultraviolet and wide X-ray range)* (Fig. 1.3).

The radiation intensity on a respective frequency of the electromagnetic waves results in a **heat flux density** (*watts per square meter of area*). Their effect on humans can be explained, in simplified terms, as follows:

- The heat flux density penetrates the skin of man as a heat **flow** (watts).
- The heat flow acts as heat (watt-second, or kilowatt-hour) within a period of time.
- The transferred heat is then stored in the body as **internal energy** (watt-second, or kilowatt-hour, or kilojoules, formerly expressed as kilocalorie).

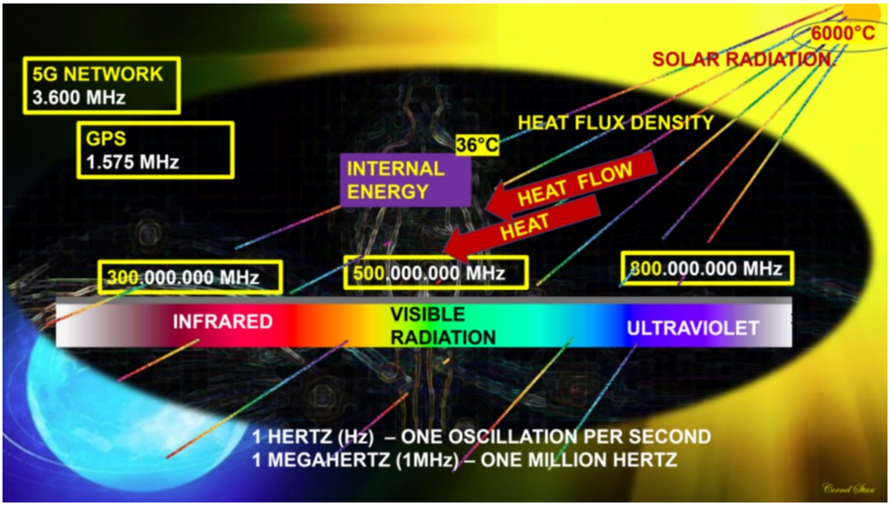


Fig. 1.3 The radiation of the sun rises internal energy of a body

However, the sun in the sky was also the source of the sacred fire, as handed down from mythology and confirmed by science.

Fire is the outer manifestation of combustion, as a chemical reaction between a fuel and oxygen. It is basically characterized by thermal radiation and occasionally by light radiation (as a flame of gases and vapors or as embers of a solid substance).

The essential characteristics of a fire can be illustrated by the following examples:

A ***chemical reaction*** *usually takes place between two substances. Meanwhile, atoms are exchanged between the substances, whereby the structure of the new product is redesigned. Such a reaction can be exothermic (with heat delivery to the environment) or endothermic (with heat input from the environment).*

Let's flambéing a cognac in a snifter with a long match: the glass becomes warm, above it appears a predominantly blue flame. The ethanol in the cognac has reacted with oxygen from the air after ignition and this mixture has become carbon dioxide and water vapor in the flame region. The still liquid fraction under the flame is slightly candied and very tasty (this experiment is not recommended for underage students).

1.3 Fire and flame

The **flame** is the heat radiation visible to humans during a combustion. Flames can occur as slow-running streaks (*laminar*) or as a swirl (*turbulent*). Each of the colors in a flame, from red and yellow to blue, corresponds to the local, instantaneous temperature in the burning mass during the chemical reaction. The higher the combustion temperature in a region of the mixture of fuel and oxygen (pure or from the air), the higher the intensity and frequency of the respective heat radiation: in terms of color it goes accordingly from infrared to ultraviolet.

Combustion with flame front, as shown in (Fig. 1.4) is a very manageable form of the process. It is given when the fuel is present, for example, in the form of small liquid droplets, which float at the same distance from each other and are each surrounded by air. If these are gasoline drops, then for the sake of the chemical balance, about 15 milligrams of air should surround a drop with 1 milligram of weight [1].

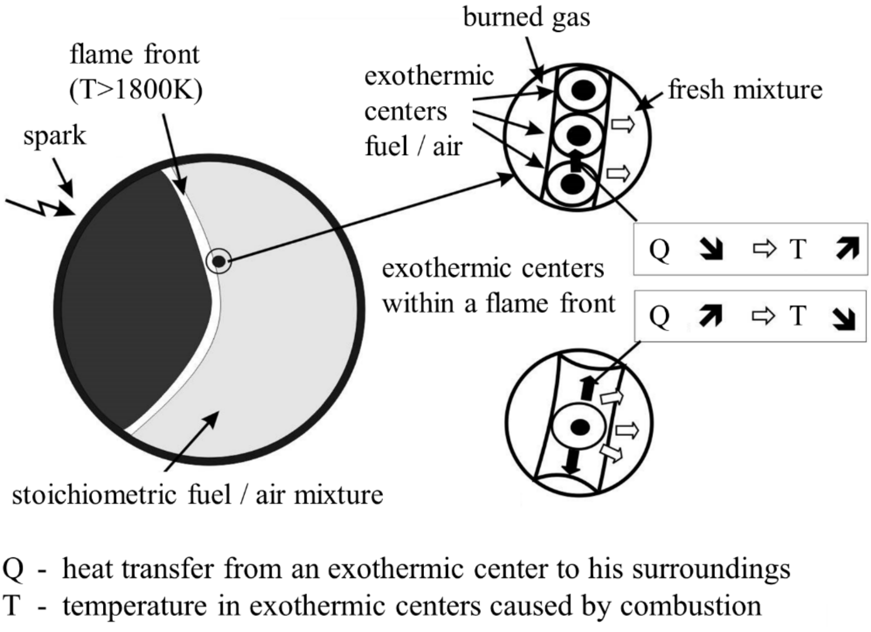


Fig. 1.4 Flame propagation into a homogeneous, isotropic fuel / air mixture

Warm air favors combustion: the fuel droplets evaporate better, which benefits the chemical reaction with the oxygen from the air. But how is this reaction set in motion? You have to bring the mixture (for liquid and gaseous fuels) or the composition of fuel and air (for solid fuels such as coal, wood or hay) up to an ignition temperature. For wood and coal, this temperature is around 300°C, for gasoline and diesel fuel about 50°C less, for ethanol 100-150°C more, for natural gas even by 350°C more.

This heating does not have to be done simultaneously in the whole mixture, it is enough to ignite locally, with a match (as in the flambéing of cognac), with a candle or, much more efficiently, with a spark plug. The chemical reaction then propagates from there in the whole mixture. The temperature of the spark in a spark plug can, for example, reach 1500 ° C, or in some versions up to 4000 ° C.

However, temperature is always an indication of the internal energy of the respective matter, in the case of sparks it is plasma. The particles in the spark burst with energy, they bang at enormous speeds in all directions. As a result, they literally whip on the chains of carbon-hydrogen-carbon-hydrogen-... in a drop of gasoline, they whip on the chains oxygen-oxygen in the oxygen molecules, on the chains nitrogen-nitrogen in the nitrogen molecules present in the air. Such original chains between the atoms of carbon, hydrogen and oxygen are broken in many places. As very reactive radicals, numerous shards and splinters are formed: *carbon-oxygen (carbon monoxide), oxygen-hydrogen (hydroxyl), nitrogen-oxygen (nitrogen oxide), or simple atoms of carbon, oxygen and oxygen.* This veritable explosion is accompanied by a temperature increase of more than 1000°C. While the free radicals look for the missing atoms of hydrogen or oxygen in their environment, their high temperature causes the ignition of the fresh mixture of fuel and air in the adjacent layer. This becomes a chain reaction, forming a wide flame front that can reproduce at high or low speeds, depending on the reaction conditions [1]. Behind the front, the search for missing atoms breaks off relatively quickly because new, largely stable molecules, such as carbon dioxide and water, have already been formed.

Many specialists in combustion engine development use simple two-zone models for the analysis of a combustion process in an engine combustion chamber: gases burned on the spark plug side, fresh mixture of fuel and air on the other side, in between the progressive flame front. In this way, pressures, temperatures or energies in each of these zones can be roughly determined in each period of a combustion process.

In real events, such a closed reaction front hardly occurs. Some splinters (free radicals) shoot further into the mixture, resulting in local foci with high temperature and pressure. You can read the temperatures or the pressures in a combustion chamber like on an Alpine map: peaks and valleys everywhere. But what is not like on the Alpine map: Both pressures and temperatures try to balance instantaneously in their immediate vicinity.

This results in turbulence on a small scale and swirl on a large scale, thereby increasing the area between fuel and air in the same volume of a combustion chamber: it is like beating mayonnaise.

Moreover, there are also atypical forms of combustion, especially in piston engines, which can be instructive in the presentation of various types of combustion in this book.

Knocking combustion, as illustrated in (Fig. 1.5) occurs in particular in spark-ignition piston engines (gasoline engines) [1].

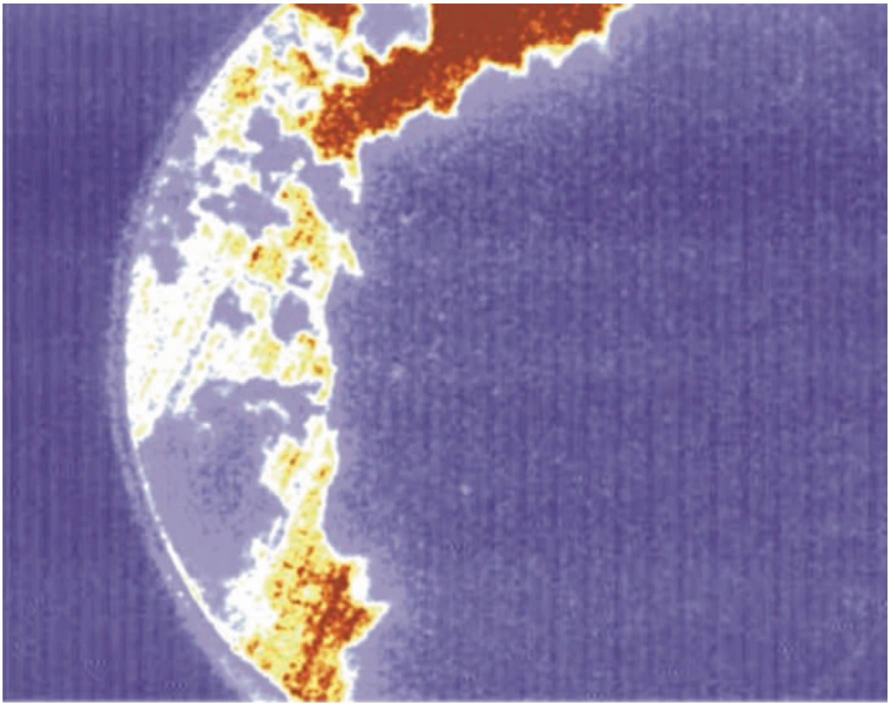


Fig. 1.5 Image of a knocking combustion in the combustion chamber of a gasoline engine

Under certain circumstances, it can pass uncontrollably in limited combustion chamber zones, at a much higher speed, around 1,000 kilometers per hour, than with the usual flame propagation (about 200 kilometers per hour). Local pressure peaks caused by knocking combustion then propagate as pressure waves into the entire combustion chamber and cause strong vibrations.

Such a process can be explained as follows: The propagation of the initially initiated normal combustion front causes a compression of the still unburned mixture, especially in the zones far away from the ignition source. A local increase in pressure and temperature leads to the abrupt breaking of long molecules chains, especially in fuels with a low octane number.

There is a good similarity with the behavior of the two-stroke engines of the GDR Trabant-cars, when nourished with low-prize, low-octane cleaning benzine.

Glow ignition happens in the most cases independently of an ignition source, generally on hot or glowing zones on combustion chamber surfaces [1]. This process develops approximately with the flame front speed of a normal combustion, which distinguishes it from the knocking combustion.

Compression ignition in advanced gasoline and diesel engines is increasingly controlled and regulated. This brings advantages in terms of consumption and pollutant emissions, in particular nitrogen oxide emissions.

In such scenarios, zones of fresh air-fuel mixture are surrounded by hot, already burnt exhaust gas, as much as possible. The internal energy of the surrounding exhaust gas initiates the combustion reaction in such individual zones.

The fact that this internal energy is much lower than the energy from a spark ignition source leads to a low combustion rate in that zone. On the other hand, such form of combustion appears simultaneously in numerous zones. This results in an entire combustion which is concurrently soft and speedy.

(Fig. 1.6) shows a schematic of the distribution of exothermic centers of fuel/air mixture as “islands” in an ocean of hot, burned gas. (Fig. 1.7) is a real image of such kind of controlled combustion by self-ignition in the combustion chamber of a piston engine, taken with an optical device.

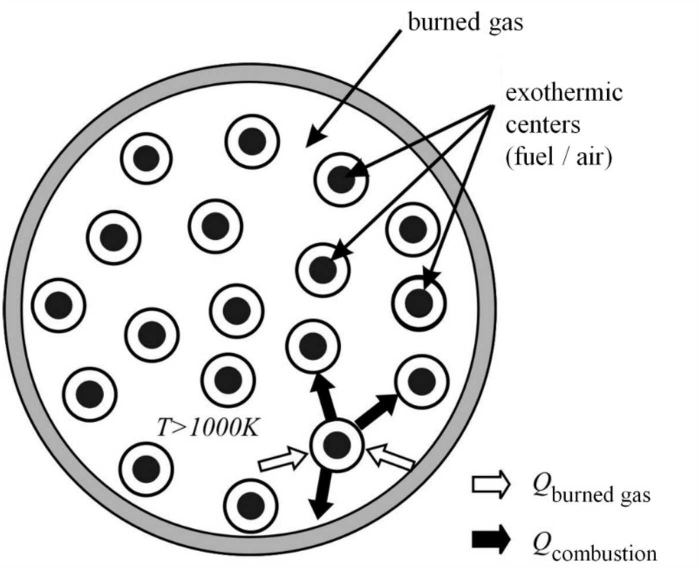


Fig. 1.6 Controlled combustion by self-ignition in exothermic centers formed by fuel and air

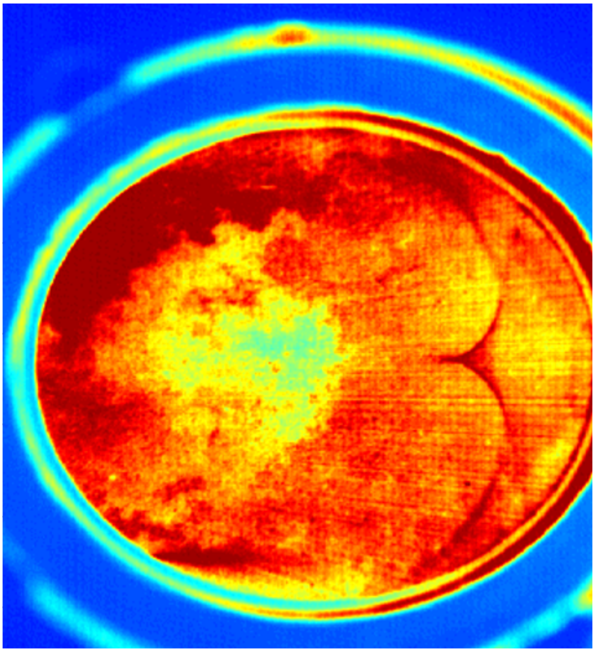


Fig. 1.7 Image of a controlled combustion by self-ignition in the combustion chamber of a piston engine

The newly developed, controlled compression ignition strategies for gasoline and diesel engines lead to efficiencies in the range of 50% and push the emissions of nitrogen oxides and other pollutants below the legal limits, even without catalysts

Combustion with diffusion flames occurs, for example, in piston engines with classic compression ignition (diesel engines) and is similar to the glow ignition described above, whereby, instead of exhaust gas *around air-fuel islands,* hot fresh air *is supplied around fuel drops* [1].

The initiation of the combustion process does not take place from an external ignition source, or from hot, burned gases: responsible for this reaction is in this case the temperature of the highly compressed air around the fuel droplets in the combustion chamber.

The reproduction of the combustion reaction is slower compared to a spark-ignited variant. On the other hand, the initiation of the reaction from the heated air in the cylinder does not require a foreign ignition source, which means that the reaction no longer propagates as a flame front staring from a unique point. Therefore, the distribution of an exact amount of air around each fuel drop is not necessary in this case. A general condition for compression ignition is the presence of a sufficient amount of air surrounding every fuel droplet. Consequently, every blob of fuel becomes a burning island in a sea of hot air.

A flame front in spark ignited combustion may be faster. On the other hand, during a compression ignition all fuel-air mixture islands burn slower, but concomitantly. Conclusion: the duration of the whole combustion decreases!

1.4 Fire usage from Homo erectus to Homo sapiens: Food preparation

The oldest attested fires by Homo erectus come from the Wonderwerk Cave in South Africa and are about one million years old [5]. The oldest man-made fireplaces in Europe, in today's areas of England, France and Hungary, are "only" 400,000 years old [6], [7], [8].

Homo erectus, however, did not invent fire itself. In reality, Prometheus did not give fire to him. It most likely came from his brother and head of the gods, Zeus, who had the power over all thunderbolts! And the thunderbolt was more of a punishment than a gift! Four to ten million thunderbolts still strike the whole earth every day, which is an average of about 50 flashes per second!

The temperature in a flash is around 30,000 °C, which is about ten times more than in the spark of a spark plug. The immediate surrounding air is heated abruptly at this temperature. A flash reaches an electrical voltage of 100 million volts and a current of about 400,000 amps. Flashes have a very short duration, it is only 0.1 to 0.2 seconds. But a flash is long, very long, between 5 and 10 kilometers!

Has anyone ever seen such a long lightning strike spearing into a large huge oak tree which stand alone in a field? The tree turned to dust in a split second, I didn't want to believe my eyes!

Homo erectus saw not only numerous thunderbolts, but also self-igniting earth fires. He thus recognized the advantages of a fire: light, warmth, protection from predators and insects of all kinds. Then there was also the grilled meat of the lightning-struck animals, it smelled as good as we know it in our time from an American steakhouse. It also tasted much, much better than the raw meat chewed until then. Smoked animals were also edible longer due to the destruction of parasites, bacteria and viruses [9].

The **friction** of wooden sticks was the simplest way to generate the heat necessary for ignition. Anyone who has ever lit a campfire in the mountains knows that the method is safe, albeit laborious.

Creating **sparks**, for example by striking a flint **(**Silex, a pebble of silicon dioxide) against a mineral rock such as pyrite or marcasite, also brought the desired success.

The **light bundling of sunlight** by hollow mirrors or by magnifying glasses has also proven itself throughout history for igniting a fire.

Light and warmth from self-lit fire were the beginning of a new era for Homo erectus. And no more raw meat, which was not only good for the stomach and intestines, but also for the jaw, which became a little thinner. This helped to better articulate consonants, making his pronunciation clearer. Over time, the food was no longer only grilled, as from lightning, but also boiled, stewed, fried, baked [10].

And that hasn't changed in a million years: the more rustic in a posh restaurant the meal is cooked, the more appreciated it is by the customers. What is a high-tech stainless-steel stove in the kitchen when compared with a stone-rimmed fire pit with an open flame on the patio, close to the table? What is a microwave versus a wood-fired brick oven in a classic Italian pizzeria?

A human is the only being in the fauna of the earth who processes most of his food by fire!

Grilling or stewing meat was only the beginning of the use of fire for human food: this was followed by cooking rice, vegetable soup and tea, smoking fish or meat, baking bread or pizza, and, not forgetting, boiling beer and burning fruit for schnapps!

Some scientists claim that the survival of Homo sapiens would have been questionable by raw food alone. Nonhuman primates needed about 10 times more time a day to eat their raw food than humans needed their cooked food. Of course, one can also argue with the academics about this:

A 5-course lunch in Tuscany takes ten times more than chewing a Big Mac from Drive In at McDonalds, although in both cases everything is cooked, fried and baked!

2

Fire for heat

2.1 Heat for space heating

In the beginning it was the campfire, which is still very popular for our “high-tech spoiled” fellow citizens. Over time, people had dwellings, with open fires in closed grottoes. This remained the case later, in built rooms. Nothing has been handed down about fires and gas poisoning from this time.

The ancient Romans found an ingenious solution in this context: fire outside, warmth inside! The system used for this purpose was called *Hypocaust.* A representative example of a Hypocaust heating system is illustrated in (Fig. 2.1). This method is still very popular today as a warm air heater. The kiln of a Hypocaust system was usually outdoors or in a separate boiler room from the house and was fired with wood or charcoal. However, the archaeologists have also found that in larger circles around Roman settlements, the forests were quite cut down!

The firing of wood or charcoal with air from the environment yielded hot exhaust gases that could circulate in the hypocaust in channels under stone cover plates, between lanes or labyrinths of brick turrets. These hot exhaust gases were then passed through shafts and canals under floors, through walls and through benches, to then be discharged into the open [11].

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Fig. 2.1 Hypocaust heating system of antiquity

In the Middle Ages, the fire was brought back directly into the house, but in stoves and fireplaces with vertical vents (chimneys), which brought the advantage of a controlled extraction of the burned gases. As a result, flue gas poisoning and soot formation in the rooms decreased significantly. Another advantage of the fireplaces was the heating of rooms over several floors, from the chimney.

In the course of the eighth century, the first kitchen ovens appeared.

And about 600 years later, the natural stones in the prints of the stoves and fireplaces were also replaced by burnt stones, then the tiled stoves appeared. The advantage of tiles made of fired clay over natural stones is their ability to store heat. To burn tiles made of clay you need fire again!

The firing with wood remained very popular in the Middle Ages, at least in Europe, the forests around larger places were then quite devastated over time, as around the ancient Roman settlements. Out of necessity, from the 16th century onwards, coal or even peat were increasingly used as a fuel substitute.

In 1716, the Swede Martin Trifvald came up with the idea of using fire to scald water, which heated the floor of a greenhouse in Newcastle, England, via pipes. That was the real birth of central heating. If it hadn't been a premature birth! As unbelievable as that seems, it took almost 230 years until after the Second World War to turn it into central heating for inhabited rooms. At the same time, for heating, wood and coal were replaced by gas and oil, which were also cheaper.

Recently, in many cases, the fireplaces have been banished from the house again, as with the Romans, although they were directly in the house from the Middle Ages to the middle of the 20th century. This is the new type of district heating, some of which has its stoves far next to industrial centers, usually in the form of combined heat and power plants.

At the moment, there are serious efforts, especially in the wealthy European states, not only to ban all sorts of fireplaces, but to extinguish them completely, in the name of the world's climate! The carbon dioxide collected in the atmosphere from the furnaces of all kinds leads to the amplification of the naturally existing greenhouse effect and thus to the warming of the earth's climate, which can have catastrophic consequences [2]. So far this is understandable, but the danger can also be averted in a completely different way.

Not the fire, but what you still burn is responsible for the increase in the proportion of carbon dioxide in the atmosphere.

Currently, fossil fuels are predominantly burned in the world: lignite, hard coal, peat, petroleum products such as gasoline, diesel fuel and heavy fuel oil, as well as natural gas [12].

According to the European Commission, the fire in the world should nevertheless be extinguished, first in the automobiles: Soon no more combustion engines may be built as drives throughout Europe! Meanwhile, however, the newest combustion engines with methanol from carbon dioxide and green hydrogen are running in large ships and with ethanol from sugar cane and plant residues in millions of flex-fuel automobiles in North and South America! This is truly climate-neutral, because the carbon dioxide emissions resulting from ethanol combustion are absorbed into new sugar cane plants via photosynthesis! [2].

However, automotive technology seems to be only the first victim of the absolute fire opponents.

As a result, they would also like to extinguish the fire in all other applications in human society: *"Let's do everything only electrically, with electricity from wind power and photovoltaics"*.

On a global scale, electrical energy currently accounts for only 15 – 17 % of total energy consumption (calculated from the annual reports of the International Energy Agency 2016 - 2019). In the production of this electrical energy, all solar plants in the world are involved with 3% compared to the use of coal and natural gas. The wind, just like oil, accounts for 7% compared to coal and natural gas, hydropower almost 10 times more than solar plants. More than 80% of the world's total primary energy demand, in which the proportion of electrical energy is taken into account, is actually covered by fossil fuels (around 23% natural gas, 27% coal, 31% oil) [2].

In addition to the interpretations of all kinds concerning "*green shares only in electrical energy consumption in any industry X*", a clear question arises: in which sectors is energy used proportionately, and how much of it is currently electrical energy in each of these sectors?

This question cannot simply be reduced to the reference of energy consumption in industry or in households all over the world to the worldwide, aggregated primary energy consumption! This depends at least on the degree of industrialization, the prosperity of the citizens, the climate and the habits in each country. In Germany, this distribution is different from China and different from Kenya.

Overall, according to official data from the Federal Environment Agency, households in Germany consumed around a quarter of the country's total energy in 2018 (in China it is 13%, in Kenya even less). Industry consumed around 30% in Germany (70% in China), transport a further 30%, trade, commerce and the service sector 15%.

Households, industry and transport in Germany thus split the lion's share of the country's energy in almost equal proportions.

Let's stay with the households: In a German single-family house (2019), a family of four persons uses over 80% of this energy for heating and hot water! On average, electrical energy accounts for around 4,000 of the approximately 30,000 kilowatt hours per year, which is around 13%. The room heat is therefore with 70% the absolute energy guzzler in the house!

And where does the room heat come from? From the fire, of course! 48% of Germans have gas heaters in their homes, around 26% heating oil heaters (around three quarters of all home heating systems burn gas or oil). Admittedly, some use district heating, which is around 14%. But how is this district heating generated for heating and hot water? Even with fire, of course. The fuels? 42% natural gas, 19% hard coal, 6% lignite.

With electrical energy, i.e. without fire, only less than 5% of German households heat.

Replacing fire from the entire energy production of a country or industry with electricity remains a utopia. You just have to offer the fire a climate-neutral food!

2.2 Heat for the production of building materials

Over time, human not only learned to light the fire, but also to grill, stew and bake his food with it. In the Neolithic age, about 10,000 years ago, he changed (*whether due to the better food?)* also his way of life, from hunter-gatherer to shepherd and farmer. And so, a dwelling, instead of the dark and damp cave, became the next station of its development. He formed for this, first with his bare hands, later with the help of cladding, cuboids of clay (*mixture of clay and sand, sometimes with parts of silt*), which he let dry in the air [13]. Over time, fibrous components such as straw, feces of cattle and horses were added to the clay. In heavy rain, however, the mud bricks softened again.

And so, the heat came into play!

Brick

The mud bricks were fired from about 6,000 BC to bricks, clay bricks or clinker. The brick mass was first mixed with a little water to be formed as a cuboid, then poured into molds, as far as the original mud bricks. But then the blanks were preheated at about 180 °C to allow the water to escape. And then the actual firing took place, at temperatures from 900°C to 1080°C, depending on the shade you wanted for the bricks. And so, the fire came back into play, ignited from fresh wood, charred wood or peat. After firing, a rapid cooling to 600° followed, then a slow cooling up to 40° C. Over time, tunnel kilns or continuous kilns with gas or electric heating were developed for brick production, in which the bricks are fired at around 1000°C for twenty hours. The higher the temperature during firing, the denser the bricks become. During the production of clinker, the firing temperature is increased to 1200°C, resulting in a very dense, smooth structure (Fig. 2.2).

Fig. 2.2 Production of bricks in Egypt, around 1500 BC

The Romans already worked with brick, later, among many other representative buildings of the world, the Prague Castle (900 AD), the Munich Frauenkirche (1494) and the Moscow Kremlin (XV century) were built [14].

Cement and concrete

Parallel to silicon-based bricks *(clay is a mixture of silicon oxides),* calcium-based cement was formed: cement (calcium oxide) is produced by burning limestone (*calcium carbonate)* at temperatures between 900°C and 1400°C.

The mixture of cement with barley grains, for example with sand, generally in a ratio of 1 to 3, produces concrete, the most important building material of our time, if not of our world at all.

The Egyptians already used burnt lime in the construction of the pyramids. In Carthage, a concrete mixture of cement and brick splinters was developed in the III century BC, which was later also used in the construction of Roman houses [15]. The Romans developed from this mixture the "Opus Caementium", from which the word cement (Italian: cemento) originated. So this was roman concrete: a mixture of burnt lime, water and sand, mixed with brick splinters and volcanic ash. Thus, for example, the dome of the Pantheon in Rome was built, with a diameter of 43 meters [16] (*the St. Peter's Basilica, as the largest church building on earth has a dome diameter of "only" 42 m!*)

Over time, clay was added to the lime in the cement. Centuries later came the reinforcement of the concrete with steel (1867).

The burning of lime in furnaces that have been or is still fired with wood, peat, coal or coke brings with it a world-threatening problem in our modern times: the carbon dioxide emission! However, this is not only due to the burning of fossil raw materials to reach the required temperature of 1400°C. Half of this emission results from the chemical transformation of the lime itself, during its heating, whereby the calcium carbonate (*lime*) is "split" into calcium oxide (*cement*) and carbon dioxide [17].

The dimension of the problem is made very concrete by two facts: Worldwide, 4 billion tons of cement are currently produced annually, resulting in 2.8 billion tons of carbon dioxide [18].

That's about 8% of the total man-made carbon dioxide emissions worldwide!

On the other hand, this makes up 3 to 4 times more than the carbon dioxide emissions of all air traffic over our planet!

In addition to dams or roads, concrete is also used to build residential buildings and buildings of all kinds, which must be heated and illuminated, in which cooking, cooling and washing are carried out. Coal, oil and gas are still used as energy sources. The overall balance becomes threatening:

The global construction and building sector accounts for 38% of global anthropogenic carbon dioxide emissions [19].

There are attempts, as in the MIT (Massachusetts Institute of Technology, USA), no longer to heat the lime, but to convert it into calcium hydroxyde via electrolysis, whereby a certain amount of carbon dioxide is also produced. And hydrolysis also requires clean electricity, if possible! However, the road to industrial application, with the quantities under discussion, is still very long!

And at the very end: If you build buildings with brick or concrete, power machines are required. And these also usually have combustion chambers that are fired with fuels.

Glass

Windows, glass facades, bottles, tumblers, glass is part of our everyday life. Like fire, glass was not invented, but discovered around 7,000 years ago. Quartz sand or quartz rock can become glass when lightning strikes or a volcano erupt. So, it's like fire! And that also brings the next realization: To make glass you need fire. About 2500 years ago, the Egyptians made glass by fire.

In the glass factories of our time, the fire is lit in melting furnaces. The glass ingredients (quartz sand as the main ingredient, plus powder of dolomite, lime, sulphate and soda) are heated to 1,600°C until they melt [20]. Again, you need a proper fire, for which all the fuels mentioned earlier, from wood and coal to gas, were and still are used. The liquid glass (glass melt) slides into a long and wide tub filled with liquid tin. However, glass is lighter than tin and floats on it like a greasy film. The resulting long, smooth glass band is then cut into large slices.

The largest glass pane in the world, manufactured for the showroom of the furniture manufacturer Wagner in Germany, has an area of around 120 square meters (20 x 6 meters) and weighs 5.5 tons. [21].

2.3 Heat for the production of metals

The control of fire clearly marked the end of the Stone Age. Man learned to melt the metals he found and mined, then to shape them with the help of fire.

Copper

6,000 years ago, people in Mesopotamia and Southeastern Europe succeeded in melting copper ore in charcoal kilns at temperatures around 1100°C. This was basically similar to burning bricks, which was used at the same time.

With the development of melting furnaces, often referred to as crucible furnaces, around the year 3000 BC, first in India and China, the casting of copper was further spread [22].

So, the people forged and poured, also with the help of fire, jewelry, objects for the household, but then also weapons. This newly created copper industry caused a veritable copper long-distance trade. Tribes and peoples got to know each other, from language and habits to food culture and interaction.

Bronze

Over time, tin was added in the manufacturing process of copper. The tin was relatively rare, so the first bronze alloys consisted of 90% copper and 10% tin. Bronze is harder and more corrosion resistant than unalloyed copper [22]. As a result, the bronze swords of our ancestors hardly blunted.

The fire for bronze production is also somewhat milder, because the melting point of such an alloy, depending on the tin content, is lower.

Iron and steel

After the Copper and Bronze Ages came iron. In the Near East, the first ironworks appeared around 1400 BC, in Europe this technique appeared about 800 years later. [27].

Iron is largely extracted in open pit mining, mostly in China, Australia, Brazil, the United States of America and Russia. The ores are processed in blast furnaces after being crushed, ground and sieved to obtain a uniform structure [28].

The iron is usually produced in blast furnaces. The process consists in a chemical reduction of the iron oxide in the iron ores. The ore is poured into the furnace with coke (carbon) in alternating layers from above. On the lower side of the furnace, air is blown in by nozzles, which was preheated at 900° C to 1300°C. This actually requires a lot of heat, which is generated in heat exchangers (cowpers) by further combustion of the flue gases from the blast furnace with natural gas. The oxygen from this hot air reacts in the oven with the coke, but in the form of combustion with a lack of oxygen [1], resulting in carbon monoxide. But it is exactly by means of carbon monoxide that the iron oxides are reduced and ultimately melted.

A look into the oven shows that the temperatures of the glowing coke are precisely stratified: where hot air is blown in, the reaction results in about 2000°C, further down, towards the furnace grate it is still about 1400°C. Further upwards, the temperature decreases: in the middle layer it is around 900°C, at the very top, where ore and coke are poured in layer by layer, it is still 500°C. In the temperature zone from 500°C to 900°C, the different iron oxides are reduced via three chemical reactions to the actual iron (ferrum), which flows out of the furnace at the bottom. The iron is liquid at 1450°C. In addition to the iron, the furnace also produces a slag (silicon and aluminum oxides, such as sand). This slag is sprayed with water and solidifies into a glassy sand, which in turn is used as a concrete filler.

Metal meets building material! Up to one ton of slag can also be produced per ton of iron produced!

But it is also possible without a blast furnace, but still with combustion. This process is called "Direct Iron Reduction" and takes place in two phases:

- An incomplete combustion of natural gas (methane) with oxygen from the air, with a defined lack of air. This results in carbon monoxide (actually like in a blast furnace) and hydrogen.

- The injection of the gases involved (carbon monoxide, oxygen, carbon dioxide and water, plus natural gas) from the bottom of a furnace, at 1000 ° C, in which the iron ore is located.

Other methods are based on the same basic reactions.

In the electric oven it is also possible, but with a high energetic price:

The production of one ton of iron in the electric furnace "costs" up to 2,500 kilowatt-hours.

Iron contains up to 5% carbon as a result of its production by one of these processes. If the carbon content is lower, below a limit of 2.06%, the product is called "steel". In contrast to iron, the steel is malleable. Iron, most commonly used as cast iron, on the other hand, is brittle but very hard.

Forging is an ancient art, developed first for the shaping of gold, silver and copper, then of steel. And for that you needed a forge fire again! Steel can be processed on such a fire from as low as 750°C with the hammer on the anvil. In modern village forges, temperatures of up to 1250°C are reached, at which the steel glows white.

The casting of metals of all kinds dates back to the Copper Age. The metal must be made liquid again after it has been produced and usually solidified as a semi-finished product (Fig. 2.3). For this, a hollow mold is required, as a negative of the outer surface of the casting. Cast iron has a mass share of 75% of the products of all foundries in the world, followed by aluminum. (*But to be fair, you have to note that aluminum is about 3 times lighter than cast iron, so in a volume comparison the balance would be equalized*!) So, back in the oven with the iron, the melting point is 1200 ° C. Different types of furnaces are used for this: cupola furnaces and electric arc furnaces, which work similarly to blast furnaces, and electrically operated induction furnaces. About two thirds of the energy requirement of a foundry is spent for melting!

Fig. 2.3 Casting iron into a mould

It would hardly be possible to mention all the areas in which iron and steel are used. Therefore, only three examples are listed here, but they are representative of our world and civilization:

- The 324-meter-high Eiffel Tower in Paris, France, is a steel structure that weighs 7,300 tons alone (without the foundation). It is composed of 18,038 iron parts by means of 2.5 million rivets [23].
- The Sydney Harbor Bridge in Sydney, Australia, is a steel arch bridge with a total length of 1,149 meters and a maximum span of 503 meters (Fig. 2.4) [24].

Fig. 2.4 Sydney Harbor Bridge, Australia

- Burj Khalifa in Dubai is a building with apartments, hotel and offices with a height of 828 meters. And this is where building material and metal meet again: Burj Khalifa was built of reinforced concrete, steel, aluminum and glass (Fig. 2.5) [25].

Fig. 2.5 Burj Khalifa, Dubai

Aluminum?

Aluminum is hardly produced with heat from the fire, worldwide mainly melt flow electrolysis is used [26].

The production of one ton of aluminum by electro-lysis “costs” an average of 16,000 kilowatt-hours, which is six to seven times more than a ton of iron produced in the electric furnace.

The largest aluminum manufacturer on earth, China, produces over 30 million tons of this metal per year. Aluminum production around the world in 2020 was 65 million tons, according to the reports of Statista.

This requires around one million kilowatt-hours (1,000 megawatt-hours, 1 gigawatt-hour).

3

Fire for work

3.1 Fire puts pressure on

The vocabulary of a fire consists of flames that can be perceived by the human eyes as red, yellow or blue, depending on the intensity and frequency of their local, instantaneous heat radiation. Flames that are invisible to humans, such as when burning hydrogen with air, indicate an even higher level of radiation intensity and frequency.

Strong thermal radiation testifies to a high internal energy of the emitting body or medium, the largest proportion of which is the kinetic energy of its microscopic particles. In the case of combustion, the medium is usually a mixture of burnt (carbon dioxide, water vapor) and non-reacting gases (nitrogen from the air).

The particles that resulted from the reaction of fuel and air after ignition burst with energy, so they pop at enormous speeds in all directions in the given combustion chamber.

These velocities can only be measured in the microscopic range by well-equipped physicists. For people with their own perceptions in the macroscopic world, “translation devices” called thermometers have been developed [1]. So, these thermometers are bridges between the microscopic and macroscopic worlds. Thermometers are filled with alcohol (as made by the Grand Duke of Tuscany, 1654), mercury (as made by the Dutchman Daniel Gabriel Fahrenheit, 1714) or with other liquids. In the case of heat transfer from the test object to the liquid in the thermometer, the liquid stretches more or less. In 1742,

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_3

the Swedish astronomer Andre Celsius presented a mercury thermometer with a measuring scale: There were exactly one hundred strokes on it. The reference points (zero and hundred) were the freezing and the boiling point of the water. And so, the unit of measurement "*degrees Celsius" (°C)* was created. Other scientists agreed on their own measurement scales and their own reference points. Thus, parallel to degrees *Celsius (°C),* the units of measurement Kelvin *(K), Fahrenheit (°F) or Rankine (° R)* were created.

***Temperature* is a perceptible and measurable expression of the microscopic movement of particles in a body or medium which exists in the macroscopic world. Temperature is not a real, physical quantity, such as a length (in meters) or a duration (in seconds), but an indirect indicator of particle energy [1].**

A fire ignited by the reaction of coal, natural gas, gasoline or schnapps with oxygen from the air causes a veritable explosion of the generated particles (Fig. 3.1). Such an increase in particle velocities on a microscopic scale is measurable in our macroscopic world as a temperature increase, often above 1000°C.

Fig. 3.1 On a microscopic scale, fire is an explosive movement of particles formed from a fuel and oxygen

The effect of a fire on a medium is also possible without direct contact. The medium can be, for example, water. In order not to extinguish the fire, it can be separated from it by a metallic separation limit, commonly referred to as a "pot". The particles in the fire shooting in all directions then drum on this boundary, which can be a metal pot wall. This transmits the vibrations by means of its own particles, to the water particles, which in turn are set into oscillation. From the outside, you can detect with a thermometer that the temperature in the water is rising.

This process is defined as a **heat transfer** from the fire over the pot wall to the water.

***Heat* is a form of energy that is transferred between two systems of different temperatures as a result of their thermal contact. Heat appears only during an energy exchange, but it cannot be stored.**

The energy storable within a system is defined as **internal energy** [1].

And if the pot has a lid? It depends on the situation: The lid can float over the water sucking or be firmly screwed to the pot. Until the same water temperature is reached, for example 80°C, more heat is needed in the pot with a floating lid than in the pot with a fixed lid [1]. This behavior will be explained in a further chapter.

As the water temperature rises, another state variable becomes increasingly noticeable in the pot, whether with a fixed or floating lid: **the pressure!** The particles in the water move faster and faster, they want to get out. They try to move the walls by their impact. The floating lid moves upwards. With the screwed lid, moving the walls seems to be in vain at first...

... two young mountain hikers arrived one day in a hut, starved *and quite penniless. They asked the host if he would permit them to eat from a tin of white beans in tomato sauce that they had with them. The merciful host took the can into the kitchen with the intention of warming up the meal. He put the can on the stove. Unopened! After ten minutes, there was a terrible bang in the kitchen, followed by the innkeeper's cry: "Take your damn beans from my kitchen!" The two hurried along, while the beans, one by one, dripped out of the ceiling.*

The movement in the microscopic range, in the can, during heating, had thus changed into a macroscopic movement of the beans after the can burst.

A macroscopic movement no longer has anything to do with the internal energy: this represents another form of energy: **mechanical work,** often called simply "work". This word corresponds to the acceleration of a mass on a distance.

***Work,* similarly to heat, is a form of energy that is transferred between two systems due to a pressure difference, at the site of their mechanical, freely moving contact. Work appears only during an energy exchange, but it cannot be stored.**

A repetition seems appropriate at this point: the energy stored or storable within a system is defined as **internal energy** [1].

People want to transfer the **heat** of fire either to the air in rooms, to the bricks in the furnace, to the metal in the melting pot *(fire for heat)* or to transform it in **work** in machines *(fire for work).* There are two variants for both heat transfer and heat transformation (conversion) in progress:

- indirect effect of fire, via a liquid or gaseous working fluid (water, air and many other media), such as in a heating system with a water boiler (for heat), as well as in a steam locomotive or in a steam turbine (for work).
- direct effect of fire, such as in the chimney (for heat), as well as in a piston engine or in a gas turbine (turbo engine) with internal combustion (for work).

3.2 Indirect effect of fire to create pressure for work

Piston engines with steam

The fire was initially used for warmth and food preparation. Soon, however, the curiosity of Homo sapiens became greater: what else can be done with fire? And so already in antiquity the first steam engine of mankind was created, invented by the Greek mathematician Heron of Alexandria around the year 60 AD. His Herons ball was the first machine using heat to create the movement of an object [2]. An open flame first heated the water in a reservoir. The resulting water vapor filled then a sphere equipped with two tangentially attached, open nozzles. The steam ejected through the nozzles each generated a reaction force, causing the ball to rotate. This resulted in work, which was, however, not used practically at the time.

Much later, in 1712, the Englishman Thomas Newcomen installed the first steam engine, which provided work in a coal mine, in Staffordshire, to pump out the penetrating groundwater [29]. In a tank, water boiled on a coal fire. The tank was connected to a working cylinder via a steam line. When a valve in the line was opened, water vapor under pressure entered the working cylinder, which pushed the piston. The machine was also equipped with a water injection to condense the expanded water vapor in the cylinder in the next step. This in turn created a vacuum that brought the piston back after expansion. The valves for letting the steam into the cylinder and for injecting the cooling water were originally operated by hand by a boy. James Watt, a mechanic at the University of Glasgow, had to repair a Newcomen steam engine one day (1764) and so he began to improve its function. Five years later, he registered a patent about "*A new invented method to reduce steam and fuel consumption in combustion engines*" [30]. Watt's steam engine was provided with a steam condenser outside the working cylinder. For this purpose, the heated steam was also directed to both sides of the piston, whereby the pressure had an alternating effect on each side of the piston. The steam engines of this kind were the true drivers of the industrial revolution! It was no longer just pumping groundwater from mining shafts. They drove mills, ploughs, looms, machines of all kinds in factories.

In 1783, James Watt came up with the idea of convincing customers for his steam engines with a clever comparison: Until then, a normal horse always pulled coal sacks or buckets with groundwater from the shafts by stretching them over ropes and reversing rollers. Watt referred to the "horsepower unit" as the vertical pull of a weight of 75 kilograms over the height of one meter within a second. And so, the "Horse-Power" (hp) was born!

The engine of a racing car currently reaches over 1600 hp. These "horses" could pull a large steam locomotive with full coal and water tenders over a meter out of the shaft within a second!

In the same year of the introduction of horsepower, in 1783, the British Richard Trevithck succeeded in transforming the back and forth movement of the pistons in Watt steam engines into a jerk-free rotation through combinations of cranks, connecting rods and gears. And so, the "Tram wagon", the world's first steam locomotive, was born. The working piston of a steam locomotive is alternately applied to the left and to the right by the heated steam. The inlet and outlet of the steam is controlled by a piston valve (above the working cylinder) (Fig. 3.2).

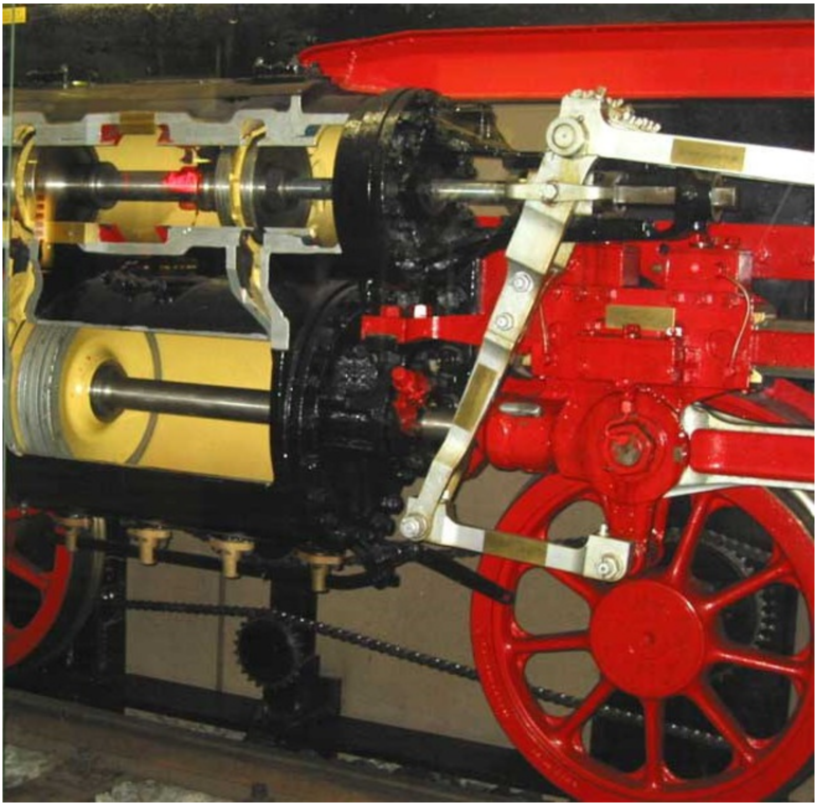

Fig. 3.2 Steam engine as locomotive drive: The working piston (bottom) is alternately pressurized to the left/right by the heated steam. The inlet and outlet of the steam is controlled by a piston valve (above the working cylinder) (Source: National Railway Museum York)

The steam locomotives and the steamships conquered the earth and the seas.

However, the water vapor heated by the fire can also be used more efficiently than by striking on a working piston, sometimes from the left, sometimes from the right, guided by piston sliders. In this case, the work gained must also be converted into rotation from the back and forth of the piston (translation) via crank and connecting rod.

Steam turbine

Why shouldn't the steam immediately hit a rotating part, whether from above, like a waterfall in a watermill, or from the side, like the wind on a windmill? However, a constant current, such as a river, a waterfall or a continuous wind, has more energy in it than "just" the internal energy, which represents the microscopic particle movement in the medium itself.

In addition to its *internal energy*, a flowing medium has a *pumping energy*, expressed in pressure and density, and, in some situations, a *kinetic energy*, expressed in macroscopic flow velocity. The collective term for all these energy components is defined as "*enthalpy*", being sometimes named also “total enthalpy” or stagnation enthalpy”, in respect to the contained part of kinetic energy.

The **enthalpy** is thus the sum of the **internal energy** and the **pumping energy** (Eq.3.1). The reference of enthalpy, internal energy and of the volume in the pumping energy to the mass of the working fluid gives the respective specific quantities (Eq.3.2). When the kinetic energy or the specific kinetic energy is added to the enthalpy or to the specific enthalpy there appears a” total enthalpy”, or a total specific enthalpy” (Eq.3.3), (Eq.3.4).

The specific volume in Eq. 3.3 is the reciprocal value of the density of the working fluid (Eq.3.5). This forms also the base of Bernoulli´s principle (1738), which shows a relationship between the static pressure and the speed of a flowing fluid, in conditions of unchanged “total enthalpy”.

$$H = U + pV \tag{3.1}$$

$$h = u + pv\,, with\ \ h = \frac{H}{m}\,, u = \frac{U}{m}\,, v = \frac{V}{m} \tag{3.2}$$

$$H^* = U + pV + \frac{mc^2}{2} \tag{3.3}$$

$$h^* = u + pv + \frac{c^2}{2}\,, with\ h^* = \frac{H^*}{m}\,, pv = \frac{pV}{m}\,, \frac{\frac{mc^2}{2}}{m} = \frac{c^2}{2} \tag{3.4}$$

$$h^* = u + \frac{p}{\rho} + \frac{c^2}{2}\,, with\ \rho = \frac{1}{v} \tag{3.5}$$

H	$[J\,;\mathrm{Nm}]$	enthalpy	h	$\left[\frac{J}{kg};\frac{Nm}{kg}\right]$	specific enthalpy
H^*	$[J\,;\mathrm{Nm}]$	total enthalpy	h^*	$\left[\frac{J}{kg};\frac{Nm}{kg}\right]$	specific total enthalpy
U	$[J\,;\mathrm{Nm}]$	internal energy	u	$\left[\frac{J}{kg};\frac{\mathrm{Nm}}{kg}\right]$	specific internal energy
p	$\left[\frac{\mathrm{N}}{\mathrm{m}^2}\right]$	pressure			
V	$[\mathrm{m}^3]$	volume	v	$\left[\frac{\mathrm{m}^3}{kg}\right]$	specific volume
			ρ	$\left[\frac{kg}{m^3}\right]$	density
pV	$[J\,;\mathrm{Nm}]$	pumping work	pv	$\left[\frac{J}{kg};\frac{\mathrm{Nm}}{kg}\right]$	specific pumping work
m	$[kg]$	fluid mass			
c	$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	fluid speed			
$\frac{mc^2}{2}$	$[J\,;\mathrm{Nm}]$	kinetic energy	$\frac{c^2}{2}$	$\left[\frac{m^2}{s^2}\right]$	specific kinetic energy

The water vapor should therefore hit such a rotating part with its concentrated enthalpy. Simply put, but from watts' steam-applied piston (1783) to the steam-laden turbine of the Swede Laval (1883), exactly one hundred years passed! A turbine unit basically consists of a stator stage and a rotor stage. Between the many blades of a stator or a rotor, both the flow cross-sections and the direction of the flow velocity can be changed by their profile design. A narrowing of the flow cross-section acts as if in a nozzle: the pressure drops, but the flow velocity increases, whereat the entire enthalpy remains unchanged. On the other hand, a curvature of the flow profile between two blades leads to a change in the direction of flow. In the rotor stages, this causes pressure on the blades, which are thereby set in rotation. Thus, the enthalpy of the flow is partly translated into work. The Laval turbine worked according to the "action principle", i.e. in the stator only pressure drop, in the rotor only change of direction of the speed. A year later, the Englishman Parsons developed a turbine according to the "reaction principle": The pressure in the stator fell only to a certain extent, in the rotor the profile design of the blade in addition to the change of direction of the flow also created a cross-sectional narrowing, as in the stator and thus an additional flow acceleration. In general, such a process takes place in stages. Several stator-rotor units are provided for this purpose. Parson was the first to install a steam turbine in a ship (called "Turbinia"). This was followed by various combinations of action and reaction modules, developed by the American Curtis, the Frenchman Rateau or the Swiss Zoelly.

Then large power plants were built according to this principle in order to generate electrical energy by converting the work obtained from steam. Just like in a locomotive, the steam is produced from a liquid, for example from water, in a steam boiler. For this, a fire must be planted under the boiler, as in grandma's bathroom on Fridays. Coal, natural gas or an oil derivative were fired for a long time. But it is also possible without fire by heating another liquid in a primary circuit by means of nuclear fission and then transferring heat to the water in the boiler, via pipes in a closed circuit. From this point on, the process runs in the same way in a nuclear power plant as in a coal-fired power plant or in a gas-powered power plant[1] (Fig. 3.3). The liquid in the steam boiler is heated (*2 to 3 temperature rises, pressure remains constant*), then evaporated (*3 to 4 temperature and pressure* *do not change, for this the vapor content constantly increases*) and finally overheated as dry steam (*4 to 5 temperature rises again, pressure remains constant*). The enthalpy of the steam is then reduced in a turbine from, for example, 150 bar/450°C to 0.05 bar/20°C (*5 to 6*) – exactly this energy is transmitted to a coupled power generator as work. The steam is then cooled in a heat exchanger (*6 to 1: cooling tower, condenser*) until it becomes completely liquid again. By means of a pump, the liquid is pumped into the boiler (*1 to 2*) and the whole process is then repeated.

The largest *coal* power station of the world, with a capacity of 6,720 MW is located in Tuoketuo, China.

The Jeber Ali Power and Desalination Plant in the United Arab Emirates, with 8,695 MW is powered by *natural gas*.

The Shoaiba power station in Saudi Arabia, powered by *fuel oil* has a capacity of 5,600 MW.

As a comparison, the *nuclear* power plant in Kori, South Korea, has a capacity of 7,489 MW.

But, in the meantime, there appeared also power stations with renewable fuels: Drax, United Kingdom is powered by pellets and has a capacity of 2,595 MW. In a lower capacity range of 200 – 265 MW there are also power plants fueled by forest residues (Alhomens Kraft, Finland), biomass (Maasvlakte 3, Netherlands), and black liquor, as a by-product in the paper industry, which contains more than a half of the energy of the used wood fed.

In reference to the enthalpy, or to the “total enthalpy”, the tremendous difference between a hot water steam obtained by the indirect effect of fire and a cold air flow blowing in a wind turbine should be mentioned: advanced off-shore wind turbines achieve only a maximum power of 5 to 10 MW (the most powerful, developed recently in China, reaching 16 MW). But they are working only for 16% to 57% of the time, does to the variable wind flow during a year.

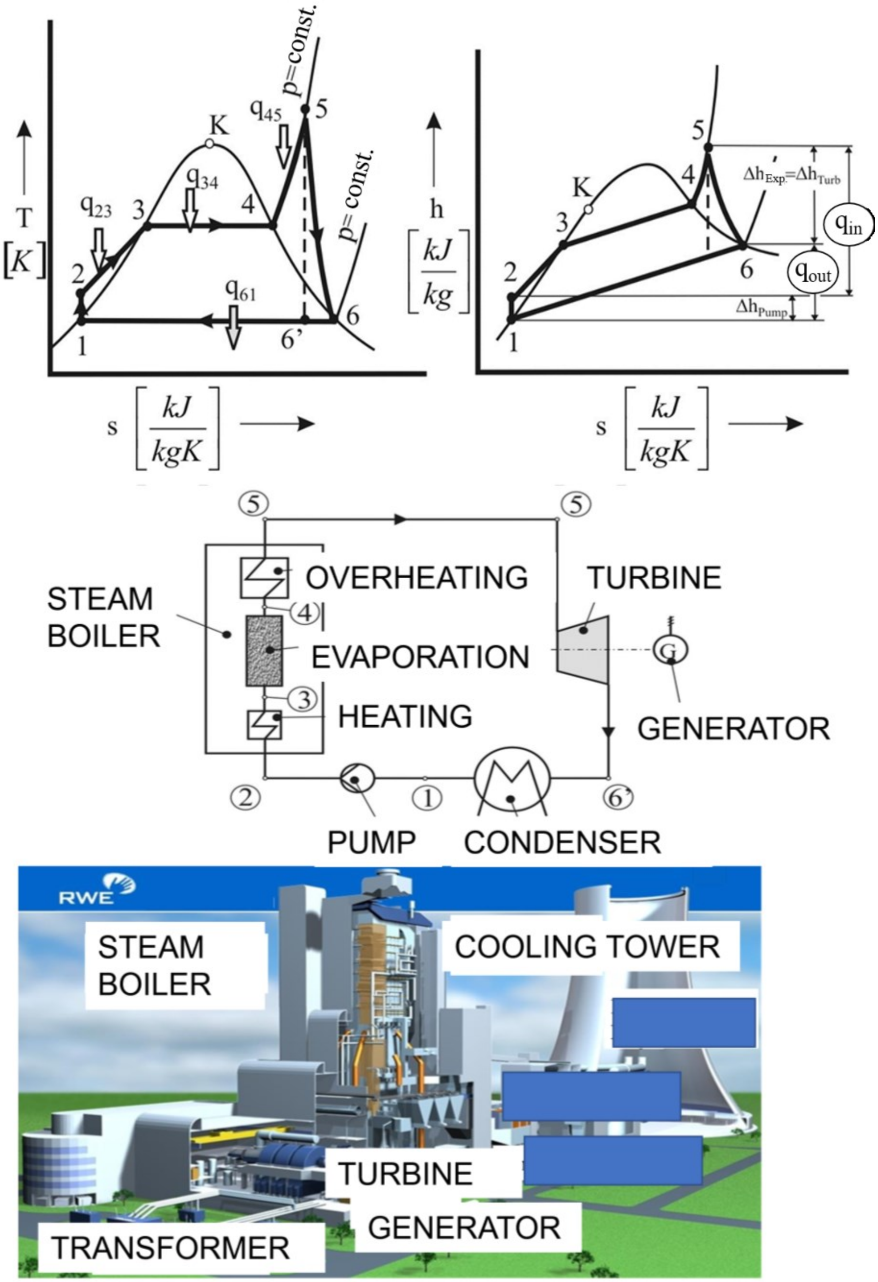

Fig. 3.3 Power plant with steam turbine (Sources: [1], RWE)

Steam turbines were also used in seagoing ships and aircraft carriers due to this high-power delivery. They are still used in nuclear-powered ships and submarines. On the large ships in this power range, however, the directly fired piston engines (diesel engines) and gas turbines have won the competition.

3.3 Direct effect of fire to create pressure for work

Piston engines

In order to ignite a fire directly in a heat engine, a liquid or gaseous fuel (*gasoline, diesel fuel, vegetable oil, liquefied petroleum gas, methanol, ethanol, natural gas, biogas, ether, hydrogen*) is mixed with oxygen (usually from the *air*) and led to the chemical reaction by spark ignition or compression ignition.

The fuel is usually cold in the reaction, the air can also be drawn directly from the environment, or brought by compression to 300 ° C - 800 ° C. Through the chemical reaction, the gaseous mixture of the reaction products (*ideally carbon dioxide, water vapor and the unchanged nitrogen from the air*) reaches temperatures in the range of 2000°C [1].

For the basic calculation of pressures and temperatures in such a process, as well as of the exchange of heat and work, it is usual to consider it as simply adding heat to the air in the engine, regardless of the fuel and the chemical reaction itself.

The first piston engine with ignition of the fuel-air mixture by means of spark plug in a cylinder with piston and crank drive was invented by Eugenio Barsanti and Felice Mateucci from Lucca, in Tuscany, in 1853 [31]. No more piston valves, as with the steam inlet and outlet in locomotive drives, but inlet and outlet valves in the working cylinder itself. The Frenchman Alphonse Beau de Rochas then submitted nine years later (1862) to the Paris Patent Office a fifty-page document describing the very first four-stroke engine in the world: *intake of air-fuel mixture by aspiration using the piston – mixture compression by piston stroke – combustion followed by exhaust gases expan-*

sion by means of piston stroke in opposite sense – exhaust gases discharge by a new piston stroke [32]. Nicolaus August Otto then acquired a patent in Germany in 1877 from the newly founded "Imperial Patent Office" on a four-stroke engine with luminous gas operation [33]. This engine was produced and marketed from 1877 under the name "Otto's new engine". Licensees in Manchester, England called it "Otto Engine". The gasoline patent was revoked in 1886 due to the previous inventions of the four-stroke engine. Gottlieb Daimler and Carl Benz were thus able to build and sell four-stroke engines without obstacles from 1886 onwards. Nevertheless, the name Otto Engine has been preserved to this day: In 1936, the Association of German Engineers coined the designation Otto Engine for all reciprocating engines with spark ignition in Germany. Ten years later, it became a veritable DIN standard.

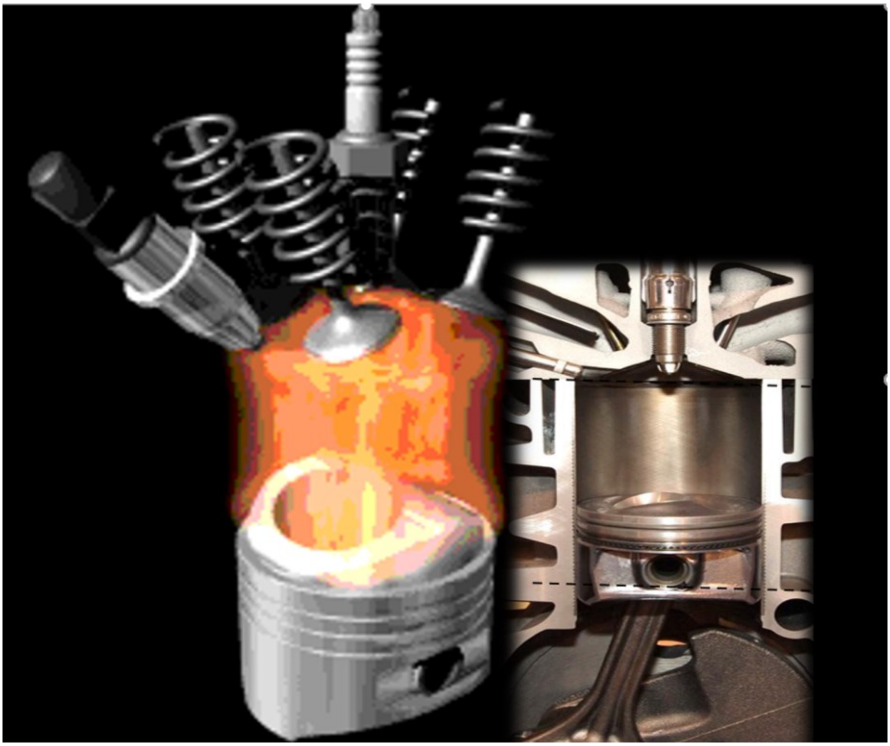

Fig. 3.4 During combustion, the temperature of the burned gas mixture formed in the combustion chamber of a piston engine increases. As a result, the pressure in the mixture increases, which pushes the piston

To this day, gasoline engines still look like they did 135 years ago, one might think: pistons with crank drive running back and forth in a cylinder encased in coolant, intake and exhaust valves, spark plug (Fig. 3.4). The development is nevertheless remarkable: Two valves generally became four, for better flow. The pistons became shorter and much lighter, the materials more resistant and friction-minimized, the speeds became much higher. Over all, the type of combustion, which depends on the mixture technique of the fuel with the air, became decisive. In the past, carburetors were used for this purpose, then low-pressure injection systems in the intake pipe, before entering the cylinder. The mixture was thus given time, the fuel could evaporate completely and mix evenly with the air before sucking into the cylinder. Then, at the end of the 1990s [34], [35] came the fuel direct injection into the cylinder after it was filled with fresh air. There is generally not much time left for this: With an engine with 6000 revolutions per minute, only 5 thousandths of a second remain for a whole piston stroke. For the injection of the fuel then only half of this time remains, in the best case, but usually less than one thousandth of a second. The fuel is then squeezed into the cylinder at 100 to 500 bar through nozzles with extremely small holes or gaps. For a complete evaporation of the drops, the time is too short, in the drops often remain liquid kernels. The homogenization of these partially evaporated fuel droplets with the air is also poor. Why do you do it then, why didn't it stay with the carburetor? Is that just because of the better dosage? By no means! The decisive factor in fuel direct injection is the huge speed at which the drops shoot into the air like tiny lead balls from the pistol. This creates powerful air turbulence around every drop, making the contact surfaces between fuel and air much larger. It's like beating mayonnaise, but with thousands, with millions of tiny whisks. The blacksmith does it the other way around, he blows air into the fire to create turbulence, and thus area between the glow particles and air. This also works well, although by means of bellows the air velocity and the air density is much lower than that of the said shooting drops. The result of a fuel direct injection is impressive: With the same air in the cylinder and even less fuel than from the carburetor, more work comes out! More work from less heat supplied means that the thermal efficiency increases considerably!

The thermal efficiency of a heat engine is defined as the ratio of the *work* done by the machine to the *heat* supplied by combustion of a mixture of air and fuel.

Certainly, with this evaporation and mixing hurry, some liquid fuel cores remain unburned or only partially burned, but the percentage is very low and they are effectively filtered out or post-treated in catalytic converters after emission from the cylinder. Current gasoline engines for automobiles achieve a remarkable efficiency of 40%. Twenty years earlier, it was only 23% to 25%! However, the heat losses caused by the cooling and by the exhaust gases must be taken into account. This heat is used in winter to heat the passenger compartment. The use of such a gasoline engine with biogas or ethanol from plant residues in a heat pump in which these heat components are used shows completely new perspectives: In such a case, the overall efficiency increases from 40% to about 80%. On the other hand, the use of climate-neutral fuels makes this engine type very fit for the future.

But there is another way as well: the piston engine without spark ignition. It is the diesel that so many “apostles” and “know-it-alls” are now demonizing in the name of the climate!

Rudolf Diesel (Fig. 3.5), expelled from Paris with his modest leather goods merchant family to England at the age of 12 because of the war, found one day alone his way back to his roots, to Augsburg. Thanks to an uncle who granted him asylum, Rudolf, who spoke French better than German, was allowed to attend a trade school, then the Technical University of Munich and complete each of them as the best [36].

The industrial school gave him a passion for mechanics and for experimentation. The lectures of the famous Professor Carl Linde let him discover the fascination of the theoretical side, the thermodynamics. Linde was notorious for its lectures about refrigeration processes and machines. He told absolutely captivating stories about heat engines, about the ideal limits of their processes, which had been explored about fifty years earlier by the French physicist Sadi Carnot. What efficiencies compared to those of the prevailing piston steam engines!

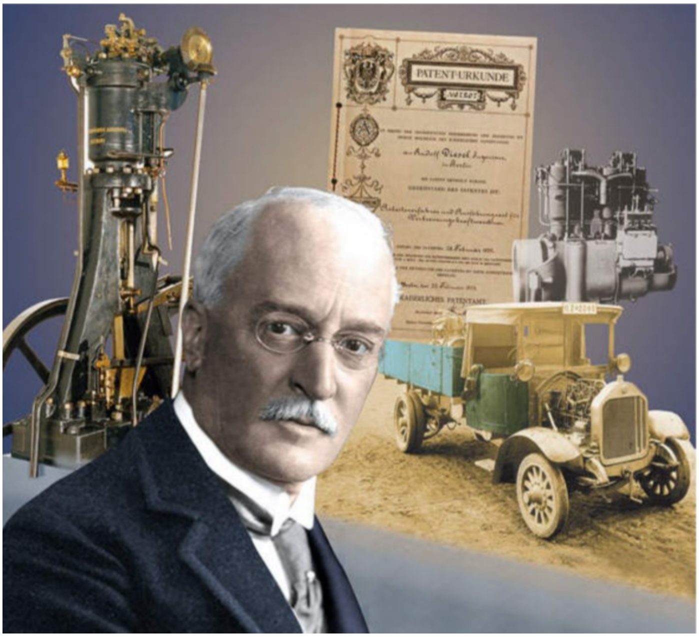

Fig. 3.5 Rudolf Diesel (1858 – 1913), his patent certificate on the diesel working method (1893) and the first functional diesel engine (1895)

On the other hand, about 20 years earlier, Beau de Rochas, Nicolaus Otto, Gottlieb Daimler and Carl Benz had been able to develop their spark-ignition engines so successfully! An engine of this type can also reach 2000°C, but only for a moment, starting from the relatively low compression, which generally does not significantly increase the maximum pressure above 80 bar.

Armed with so much theoretical and practical knowledge, the young Rudolf Diesel began its battle with the efficiency of the heat engine. The Frenchman Carnot based his own theoretical cycle on a maximum, constant temperature during the entire heat supply. So, the combustion should start right at 2000 ° C! How can this be achieved? By previous compression of the working fluid, for example the air, up to such a temperature? This would cause pressures above 5500 bar, too much for machine, screws, materials. A compression ratio of 700, instead of about 7, as with the gasoline engines of that time? And then to keep the 2000°C even during a first phase of gas expansion within a cylinder?

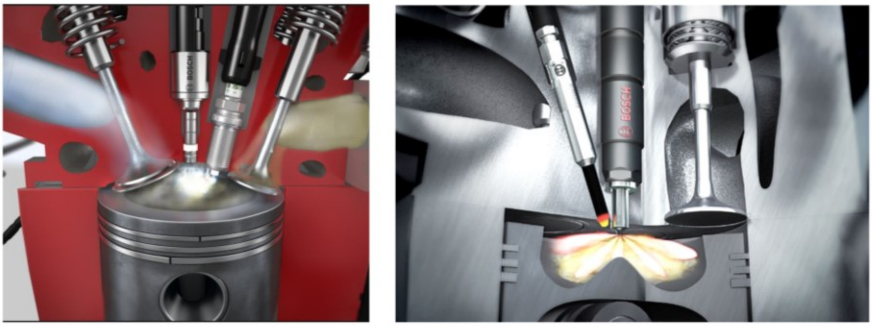

Fig. 3.6 Gasoline engine with flame front by spark ignition (left) and diesel engine with simultaneous combustion in the entire chamber by compression ignition (right) – modern versions with fuel direct injection in combustion chamber (based on Bosch models)

Diesel achieved a compromise between the Carnot and Otto cycles by creating a combustion process at constant pressure. The idea was that the maximum pressure can remain at the approximately 80 bar, like the pressure peak during the Otto process. The solution was the self-ignition of the fuel injected directly into the combustion chamber, due to the high temperature of the air, which was compressed much higher than in the gasoline engine (Fig. 3.6). The combustion process is in such circumstances certainly slower than in an engine with spark ignition, which is disadvantageous in terms of efficiency. On the other hand, both the temperature and the pressure level during the heat supply are higher than in the spark ignition process. As a result, the efficiency is significantly higher and therefore the fuel consumption is lower than with a spark ignition engine, and much higher than in a steam engine.

After numerous and expensive experiments, Rudolf Diesel applied for a patent on "Working method and implementation of internal combustion engines", which was notarized by the Imperial Patent Office with the date of February 23, 1893 [37].

On August 10, 1893, the 35-year-old Rudolf Diesel managed a first, powerful bang after the fuel jet was injected into the hot air within the combustion chamber. It worked, indeed! This test was followed by experiments with violent explosions, dropouts, clouds of soot and jets of fire from the exhaust pipe. After a good four years of intensive and nerve-wracking work by Rudolf Diesel and some engineers, the breakthrough was achieved on February 17, 1897: 20 hp and 26.2% efficiency, while a steam engine of the same power produced only 10%!

However, Rudolf Diesel was in too much of a hurry to commercialize his invention: In the following one and a half years, licenses were granted to 20 companies worldwide. However, many design and manufacturing errors led to medium to large functional disasters, which brought him a lot of trouble.

In 1902, hundreds of diesel engines ran in factories, electricity and pumping stations and hotels, and the following year on ships. Twenty years later, diesel engines powered tractors and trucks, and in 1936 the first automobile was also equipped with a diesel: Mercedes Benz 260D.

The thermal efficiency of diesel engines, as the reciprocal term of fuel consumption, reached twice the value in a hundred years. Currently, it surpasses in cars and trucks engines with 40-50%, those of all other heat engines, starting with gasoline engines which achieve only 30-40%. Gas and steam turbines with outputs above 100 megawatts can reach similar values of 40-45%. Only power plants with combined gas-damp cycles with a power range of 100-500 megawatts achieve higher efficiencies of 55-60%.

Some time ago, the potential of the diesel process was experimentally proven, even with diesel engines from the current production when implementing an exact modulation and control of the combustion process: By splitting the injection quantity per cycle into five to eight portions and the correspondingly adapted injection start, the local temperature peaks in the combustion chamber, which are responsible for the formation of nitrogen oxides, can also be eliminated. Under real conditions, in vehicles on the road equipped with such engines, nitrogen oxide values were measured that reach just one tenth of the European standard.

So, it's possible! The diesel process will live on, and how! Renewable fuels such as methanol, ethanol and dimethyl ether from algae, plant residues and household waste, as well as its cooperation with electric motors in ensuring the propulsion of a vehicle will give it a further shine.

Turbomachinery (gas turbines)

Leonardo da Vinci from Tuscany, the true universal genius of all time, invented a gas turbine in 1500, which turned out of a chimney by means of hot gas and drove a roast skewer via a tooth chain connection [38].

The Englishman John Barber received a patent in 1791 for the first gas turbine whose most components can also be found in modern gas turbines [39]. This turbine powered a carriage.

Charles Gordon Curtis patented in 1899 the first gas turbine engine in the USA ("Apparatus for generating mechanical power" [40]. After 1937, the first turbomachinery-powered military jets appeared in Britain and Germany [41]. In 1943, Messerschmitt Me 262 was the world's first mass-produced jet engine aircraft [42].

The gas turbines have the mechanical advantage of a pure rotational movement compared to the piston engines. In addition, there is also a remarkable functional advantage:

In a turbomachinery (gas turbine), all process stages, from air intake and compression to combustion, expansion and exhaust of the burned gas take place simultaneously, everyone in a functional module developed and optimized for this purpose.

The intake diffuser, compressor, combustion chamber, turbine, and exhaust pipe therefore, have their own specific characteristics (Fig. 3.7).

On the other hand, the piston-cylinder unit of a piston engine acts once as a compressor, then as a combustion chamber, as an expansion module and as a scavenging system. The compromises are in this case inevitable.

The implementation of a stream machine process can take place in a turbomachinery with axial compressor and turbine (Fig. 3.7), (Fig. 3.8), or in a machine with radial compressor and turbine (Fig. 3.9), (Fig. 3.10) [3]. The axial compressors-turbine modules are generally used in aircraft engine construction (jet engines), while the radial combination compressor-turbine could find a more efficient implementation in automotive engineering due to its already wide application as turbochargers for piston engines, when supplementing it with a combustion chamber.

The principle of operation of both forms is similar.

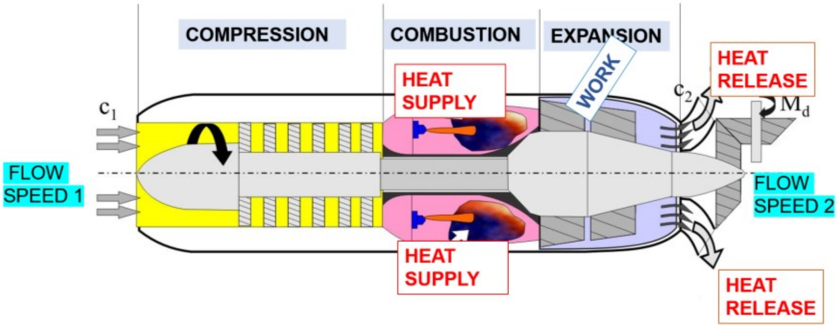

Fig. 3.7 Gas turbine with axial compressor and turbine unit – schematic

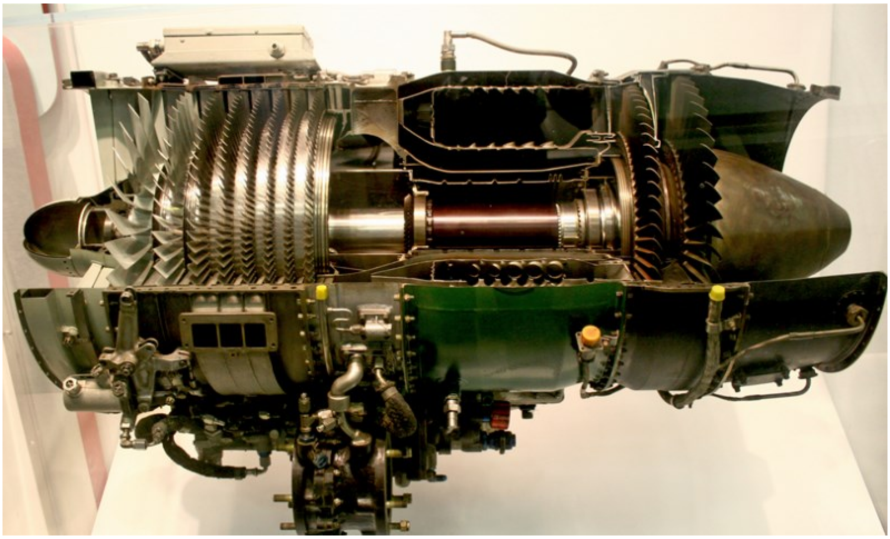

Fig. 3.8 Gas turbine with axial compressor and turbine unit – cross section

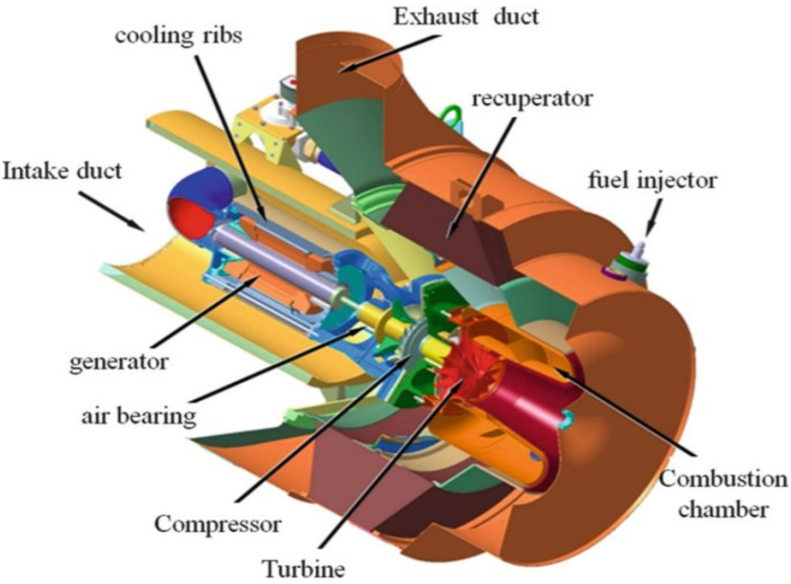

Fig. 3.9 Turbomachinery (gas turbine) with radial compressor and turbine unit – schematic (Source: Capstone)

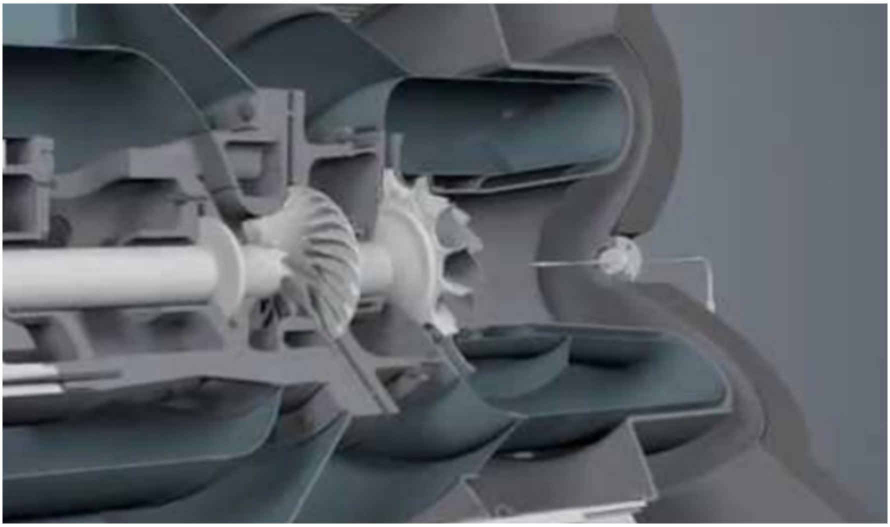

Fig. 3.10 Gas turbine with radial compressor and turbine unit – section (Source: Capstone)

The compression is usually carried out by means of an axial compressor (Fig. 3.7), (Fig. 3.8) using several compressor stages with rotor and stator modules. Combustion takes place in an open combustion chamber at constant pressure as a result of the continuous mass flow of air and fuel. The mixing and combustion of fuel and air in such a chamber, compared to those in the closed combustion chamber of a piston engine allow a remarkable process optimization: As a result of the continuous mass flow, the fuel injection nozzle is always open, so there is no fast-opening and closing needle, as in the nozzles of the injection systems for piston engines. The fuel is usually passed through with a swirl, which provides a stable jet and good atomization [3].

The penetration depth of the beam and its propagation angle do not play a major role anyway: There are no limits of geometry of the combustion chamber. The contact surface with the sheathing air can thus be optimally designed. In most cases, the largely cylindrical jacket of the combustion chamber on its outside is enveloped by a secondary air flow derived from the same compressor. On the one hand, this defuses the thermal load on the combustion chamber and dampens lateral heat losses. On the other hand, in zones of the combustion chamber where the flame temperature rises to such an extent that nitrogen oxides could be produced locally, holes can be drilled into the combustion chamber jacket: The suction of part of the secondary air flow through such boreholes leads to a local reduction of the temperatures in the endangered area.

The expansion of the burned gases occurs, in general, across a multistage turbine. The first turbine stage or stages serve to ensure the compressor work, which is transmitted to it via an axial shaft. The second turbine stage or stages – convert the remaining enthalpy of the working fluid into the actual useful work. This work can be utilized by means of a gearbox for the direct propulsion of a vehicle or to generate electricity in a generator [3].

In this manner, the exhaust gas is relieved up to the ambient pressure, but still has a higher temperature than that of the environment. The heat still contained in it can be collected and reused via a heat exchanger.

3.4 Fire directly or indirectly, on pistons or in front of turbine?

The variety of process types and machine designs seems to be overwhelming:

- Should the working fluid, whether air, water, or another fluid, first be heated separately and indirectly, as in the steam locomotive, in the power plant or in a Stirling engine [1], [3]?
- Should the working fluid, such as the air, be fired with fuel directly in front of the piston or in front of the turbine?
- Should the working fluid be temporarily enclosed in a combustion chamber and complete there one process sequence after another, as in four-stroke, two-stroke or Wankel engines [1], [3]?
- Should the working fluid act as a flow through task-specific modules, such as in power plants or in turbomachinery (gas turbines) [1], [3].

In such a thicket of variants, is it still possible to find the right way to produce work by means of fire?

Yes, you can if the process and the machine design are centered on the intended use. It is a nonsense to install a hydrogen four-stroke engine or a gas turbine in a moped instead of the usual, small, compact and inexpensive two-stroke engine (preferably with biofuel direct injection), just for the sake of technical sophistication. It is just as nonsense to install in a very expensive and fast car with well over 1000 hp a sixteen-cylinder four-stroke engine weighing over 600 kg and also large in W arrangement. It is smarter to instead provide two compact gas turbines that supply electrical energy as stationary power generators for four compact drive electric motors. The price and the acceleration behavior of the respective car are almost the same that with the W-engine monster, but there are enormous differences in terms of fuel consumption and pollutant emissions. Both versions were practically realized and tested on the road with considerable success. The two competing car manufacturers are not unknown internationally.

A certain process is not improved when more and more complicating the machine design. The best example was the carburetor, which has to dose fuel. Over time, he had to adapt to a variety of operation and atmospheric conditions. An additional bore was drilled, then an extra nozzle added, and moreover, a pressure compensation module. Thus, the carburetor became a hydraulic-pneumatic, structurally very complex precision clock. But one day, appeared an electrically powered fuel pump and a simple, electromagnetically operated and electronically controlled injection nozzle[34]. That was in fact the end of the carburetor.

A process-related revolution is usually more efficient than a construction-related, often very cumbersome evolution.

4

Climate-neutral fuels

4.1 Resources, potentials, properties

The sun is constantly burning. It sends its thermal radiation as a bundle of electromagnetic waves in all directions, including to Earth. The continuous burning on the sun does not require oxygen, which does not exist around the sun anyway. It is a combustion by fusion of the hydrogen nuclei into helium nuclei, as on other stars.

People have been dreaming of *nuclear fusion* like in the sun for a long time. It is only uncertain how they would deal with it if they could control it.

The black powder, as an explosive, does not need oxygen from the outside, it consists of saltpeter, which itself contains oxygen as an oxidizing agent, as well as carbon, charcoal and sulfur.

Black powder or similar mixtures without oxygen from the air in the heating furnace, piston engine or gas turbine would lead to explosions and destruction. They are only used as a driving force for weapons and missiles.

In most other applications, people use fuels that oxidize with oxygen from the ambient air. Such a chemical reaction then produces warmth, which can be utilized for heating or converted into work by means of thermal engines. With the work, machines and motors are driven, or electric current is generated.

People on earth still use both fossil and renewable fuels. They can be solid, liquid or gaseous [1], [3]:

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_4

Solid - Coal, Biomass
Liquid - hydrocarbons, alcohols
Gaseous - hydrocarbons, hydrogen

Of considerable importance for the preservation of the climate on earth is first and foremost the origin of a fuel.

Fossil fuels (organic structures that have been converted into hydrocarbons over millions of years) are only available to a limited extent under their current intensive use. However, the reason for their mandatory replacement is different: their conversion, mainly into carbon dioxide and water as a result of combustion, changes the composition of atmospheric air. The carbon dioxide produced from fossil fuels is not naturally recirculated in the atmosphere. Nevertheless, fossil fuels also have clear advantages, such as the comparatively uncomplicated conversion to utilizable fuels in thermal machines, the ease of transport and storage and the high energy content per unit mass or volume.

Renewable energy sources from plants, on the other hand, are available indefinitely. Their transformation by combustion is part of a natural cycle, which only partially affects the composition of atmospheric air. Renewable energy sources offer a secure perspective for the further use of energy for heat, mechanical work and electricity.

The most widely used fossil and renewable energy sources and the fuels produced from them are the following [1], [3]:

fossil sources	***utilizable fuels***
coal	*synthetic fuels, hydrogen*
petroleum	*gasoline, diesel fuel, liquefied petroleum gas*
natural gas	*CNG (Compressed Natural Gas)* *LNG (Liquified Natural Gas)* *hydrogen*

renewable energy sources	***utilizable fuels***
waste products	*biogas*
biomass	*methanol, ethanol*
vegetable oils	*diesel-like fuel*
water	*hydrogen*

A fuel contains one or more of the following elements: *carbon, hydrogen, sulfur, oxygen, ballast.* Depending on which of these elements are present in a fuel, its complete combustion with oxygen from the air results in: *carbon dioxide and water vapour,* in some cases also *sulphur dioxide*.

The following characteristics of a fuel are decisive for its use in the generation of heat or work [3]:

- *Molecular structure (number of carbon, hydrogen and oxygen atoms)*: *It* directly affects the structure and concentrations of the exhaust gas components as a result of the mass fractions of carbon and hydrogen in the combustion reaction. For example, the combustion of pure carbon results in the maximum carbon dioxide concentration per kilogram of fuel; on the other hand, the combustion of pure hydrogen does not produce carbon dioxide, but only water.

  Natural gas has more hydrogen atoms in relation to the carbon atoms than *gasoline.* The combustion of one kilogram of natural gas results in less carbon dioxide than one kilogram of gasoline, but both fuels have almost the same calorific value.

- *Fuel density:* The volume, but also the mass of the overall fuel tank system, depends on this.

  Gasoline, diesel, methanol, ethanol and the oil ethers have widely a similar density at ambient pressure and temperature. Simple and inexpensive tanks are sufficient for their storage.

LPG comes at a reasonable pressure of 5 to 10 bar, in liquid phase, near this density.

Natural gas has about a fifth of the density of gasoline but only at a pressure of 200 bar, at ambient temperature. At very low storage temperatures, by minus 150°C. at ambient pressure, it just reaches more than half the gasoline density.

Hydrogen poses a considerable problem in terms of storage volume due to its density. Under the same pressure and temperature conditions, for example, around 15-times less hydrogen (in grams) than air (in grams) can be stored in a tank with similar volume! The stored mass can only be increased in a given volume if, on the one hand, the pressure is increased, on the other hand, the temperature is lowered [1].

- *Viscosity (viscosity) of the fuel: It* primarily affects the combustion process. Oils, for example, have around twenty times the viscosity compared to diesel fuel. Even by the chemical "shortening" of their molecules (transesterification) the viscosity is lowered. However, it still remains twice as large as that of diesel fuel. The combustion of a freshly pressed oil injected through an intermittently opening nozzle can lead to coking phenomena at the nozzle outlet and a short time, later to nozzle clogging.
- *Calorific value of the fuel (the heat that can be recovered from it as a result of the combustion of one kilogram):* This calorific value depends on the mass fractions of carbon, hydrogen and oxygen in the fuel. For example, with the same amount of fuel (kilograms), the range of the same vehicle with the same combustion engine with the same power requirement would be about three times as long when burning hydrogen than when burning gasoline. Unfortunately, however, the density of hydrogen, whether stored cold or under pressure, is much lower than that of gasoline, so that much less mass can be absorbed in the same volume.

  In the transition from gasoline to methanol, the range would be reduced by half with the same tank content. The latter case largely corresponds to real conditions, due to the comparable density of gasoline and methanol under the same storage conditions (ambient state).

- *Air-fuel ratio (chemically required air requirement of the fuel):* The air demand, like the calorific value, depends on the mass fractions of carbon, hydrogen and oxygen in the fuel [1]. A fuel made of pure hydrogen requires the largest air mass for a chemically exact reaction. Alcohols already contain a proportion of oxygen and therefore, as a comparative example, include less oxygen from the ambient air in the combustion than gasoline.
- *Calorific value of the fuel-air mixture:* This calorific value of the mixture cannot be compared with the *calorific value of a fuel mentioned* above. An example: The calorific value of hydrogen exceeds the calorific values of all other fuels, which theoretically suggests more heat delivery when burning. However, the air requirement of hydrogen is very high [1]. And so the calorific value of a hydrogen-air mixture is even slightly lower than that of a gasoline-air mixture.

  This means, as an example, that the switch from gasoline to hydrogen in a piston engine does not lead to a spectacular change in torque.

These relationships clearly show that the physical properties of the fuels influence both the process development and the heat to be expected from it when burned with air.

Much has been written and said about the properties of fossil fuels such as gasoline, diesel fuel, natural gas, heavy fuel oil or coal. They still dominate the energy world, whether in transport, industry or space heating. But these atmospheres killing fossil fuels hardly have a future, so they are not considered further in this book.

On the other hand, gaining enough work and heat from wind power and photovoltaics by converting it into electrical energy sounds rather illusory. There is a clear conclusion: Keep on running by clever burning. Alcohols, biogas and oils have considerable potential in this context: they can be produced centrally and decentral, in large and in small inexpensive plants, easy to store and can be used in heat engines as well as in heating systems without any problems.

4.2 Biogas (methane)

Winning

The biogas contains between 50% and 75% methane from organic raw materials and is a promising renewable substitute for the natural gas still used in large quantities worldwide [3]. Biogas and natural gas can be mixed in any ratio up to a complete substitution of the natural gas. For both gases the same infrastructure and storage equipment can be used. Heating systems and heat engines work just as well with biogas as they do with natural gas. The biomass that can be fermented in the world is very diverse, from sewage sludge, biowaste, food residues, manure, manure, plant residues to the various energy crops.

As an example: a small village biogas plant in Europe converts 55 tons of cow manure from a neighboring farm into 370 kilowatt hours of electrical energy every day. With this electrical energy, the batteries of eleven compact electric cars could be fully charged [3]. For cars with combustion engines, however, biogas, meaning methane would also be very suitable without conversion into electrical energy. The is obviously also the easier way.

Properties

Due to the similarity of *calorific value, air-fuel ratio and mixture calorific value* with those of gasoline, a conversion of combustors and gasoline engines to methane operation is widely unproblematic.

Storage

In addition to gaseous storage under pressure, known from natural gas operation as CNG (Compressed Natural Gas), the LNG (Liquefied Natural Gas) form is also used: at minus 161-164 °C and atmospheric pressure, the natural gas is liquid. Its density is then three times higher than at ambient temperature, but this state requires an increase in technical effort (cryogenic storage technology). Notwithstanding this, the use of liquefied methane (LNG), currently as natural gas, later as biogas, has good perspectives. LNG is increasingly used in marine propulsion systems. Due to the mentioned strong cooling at ambient pressure, which determines the phase change from gas to liquid, the methane volume is reduced to 6% of the original, gas phase. Compared to an increase in pressure to 200 bar at atmospheric temperature, as in the case of CNG, the LNG volume is 3 times lower, which allows a better storage. This solution is primarily used in LNG tankers, which transport the liquid gas anyway. Currently (2019) there are a total of 321 ships with LNG propulsion (plus 501 new orders), of which 224 LNG tankers, 44 other tankers, 12 LPG tankers, 22 offshore ships 8 container ships, 2 car transporters [3].

In road traffic, LNG was used till now only in commercial vehicles due to the cost-intensive cryogenic storage. In 2019, the vehicle manufacturer Scania introduced such a truck with an LNG engine with 302 kW in series production. The basis is a series diesel engine, which has been redesigned for spark-ignition, with a lower compression. The range, only for the towing vehicle, is 1,000 kilometers. The vehicle manufacturer IVECO has brought a similar configuration with an engine with 339 kW at the same range as Scania into series production. Bio-LNG-Euronet offers Scania and IVECO a liquid biogas plant that supplies numerous filling stations throughout Europe. A special LNG engine variant was developed by Volvo: The engine works as a self-ignited diesel, being derived from the company's successful series diesel engine. The advantage of this solution is the high thermal efficiency, which is characteristic for diesel processes. The compression ignition is realized in this case by the pilot injection of a small amount of diesel fuel [3].

And that's not all: A promising technology – ANG (Adsorbed Natural Gas) – consists in the adsorption of the gas in an activated carbon matrix at pressures of 40 to 70 bar. It's going to be exciting!

4.3 Alcohols: Ethanol and Methanol

Manufacturing

Nikolaus August Otto already utilized ethanol in his engine prototypes in 1860, Henry Ford used bioethanol between 1908 and 1927 in series-production vehicles and described it as “the fuel of the future”.

Ethanol and methanol are obtained from two groups of feedstock [3]:

- *Starch and sugar* from plants. For example, sugar cane molasses is used in Brazil, corn in North America, sugar beet and partly wheat in Europe, cassava in Asia.
- *Algae and cellulose* from residues of the paper or wood industry, from vegetable waste and from plants unsuitable for human consumption.

The potential of these resources and their influence on the human and natural environment in their systematic utilization as fuels in the form of methanol or ethanol can be demonstrated in base on the following facts and examples [3]:

Sugar cane has been cultivated in Brazil since 1532. Ethanol from sugar cane was already used there as a fuel for automobiles between 1925-1935. Since 1975, after the 1st global oil crisis, the Brazilian government has consistently pursued the national alcohol program ProAlcool to replace fossil fuels with alcohol. The first standard car to run on 100% ethanol since the introduction of the ProAlcool range was the Fiat 147 (1979). Ten years later, 4 million vehicles in Brazil were running 100% ethanol. The reversal of this trend in the following years towards more dependence on oil had primarily foreign economic policy causes. However, this situation was overcome relatively quickly. From 2003, the Brazilian VW Gol 1.6 Total Flex was introduced to the market, a car for variable mixtures (0-100%) of gasoline and ethanol (Flex Fuel). Seven years later, Flex Fuel vehicles of Chevrolet, Fiat, Ford, Peugeot, Renault, Volkswagen, Honda, Mitsubishi, Toyota, Citroen, Nissan and Kia were on the Brazilian market. This accounted for 94% of all new registrations!

In 2017, 29 million Flex Fuel vehicles were driven in Brazil. This intensive use of ethanol from sugar cane certainly raises the question of the availability of resources. Brazil has 355 million hectares of arable land, of which only 72 million hectares are currently cultivated. Sugar cane is planted on only 2 % of the said arable surface. On the other hand, only 55% of this sugar cane are utilized for ethanol production. Brazilian scientists assume that cane sugar cultivation can be increased 30-times without affecting the environment and without endangering food production. Productivity is up to 8000 liters of ethanol per hectare (2008) at a price of 22 US cents/liter. Ten times more energy (in the form of ethanol fuel) is obtained than the energy used in the entire process between sugar cane cultivation and the production of the corresponding amount of ethanol.

99,7 % of Brazil's sugar cane plantations are located on plains in the southeastern region of Sao Paolo, which is at least 2,000 kilometers from Amazon's tropical forest, where the climate is rather unsuitable for sugar cane.

In the USA, ethanol is mainly produced from grain and corn. This requires 10 million hectares, which is 3.7% of the arable land [3]. Productivity is up to 4000 liters of ethanol per hectare (2008), half compared to production from sugar cane in Brazil. The energy balance between ethanol as a fuel and ethanol production is only 1.3 to 1.6. This is rather low compared to the value 10 for sugar cane. The basic price of 35 US cents/litre is higher than when using sugar cane (22 cents). Ford, Chrysler and GM build Flex Fuel powertrains across their entire vehicle range, from sedans and SUVs to off-road vehicles. There are currently 10 million Flex Fuel vehicles in the USA. A current US government program envisages to increase the production of cellulose ethanol from residual agricultural products, from residues from the paper industry and from household waste in the coming years.

In addition to *sugar cane, grain, corn, sugar beet and cassava,* algae represent an important source for the production of alcohol. Algae are aquatic creatures that feed on the basis of photosynthesis. The yield per area – but when cultivated in algae reactors – is significantly higher than for the production of biomass in agriculture: it is 15 times compared to rapeseed and 10 times compared to maize. Research is currently very active in this field. Several companies such as Boeing and Exxon are significant examples in this context.

Production

Alcohols can be produced by one of the following two methods [3]:

- Distillation of fermented biomass,
- Synthesis, via gasification and reaction using cyanobacteria and enzymes

Alcohol was distilled from wine as early as 925 by the Persian physician Abu al-Razi. However, the natural origin of alcohol in the fermentation of sugary fruits was noted much earlier by people, as mentioned in ancient Egyptian and Mesopotamian scriptures, but also in the Bible. The production of alcohol from biomass is similar to that used for the production of fruit, rum, whisky, vodka or sake – as representatives of all continents – from fruit or vegetables. In Japan, sake from fermented rice was obtained as early as the 3rd century BC. In the 10th century, the distillation of wine from lychee and plums for the production of high-proof spirits was widespread in Anatolia (Asia Minor). The overproduction of grain in the middle of the 18th century led to a large-scale production of gin in England.

The simplest form of distillation consists in the cooking of fruit, which decayed within a few weeks with free storage, followed by the condensation of the resulting steam by means of external cooling of the steam pipe, for example with a flow of cold water, and supply of the resulting liquid alcohol to a vessel. This simple presentation is only intended to emphasize that such a technology is light and easy to control and that it can be used anywhere in the world in large-scale plants or in decentralized manufactures. Industrially, the sugary mash from the fermented raw material, which already has an alcohol content of 10%, is brought by distillation/rectification to a concentration of more than 99%.

A particularly interesting alternative is the production of ethanol from waste containing hydrocarbons. This also includes old tires or plastic containers as well as organic waste (Fig. 4.1).

The hydrocarbon structures in the waste are converted into a synthesis gas by cracking. The chemical energy in the contained proportions of carbon dioxide and hydrogen is then used by microorganisms in a bioreactor to produce ethanol. The microorganisms show an increased tolerance to impurities that would inhibit a classical chemical transformation.

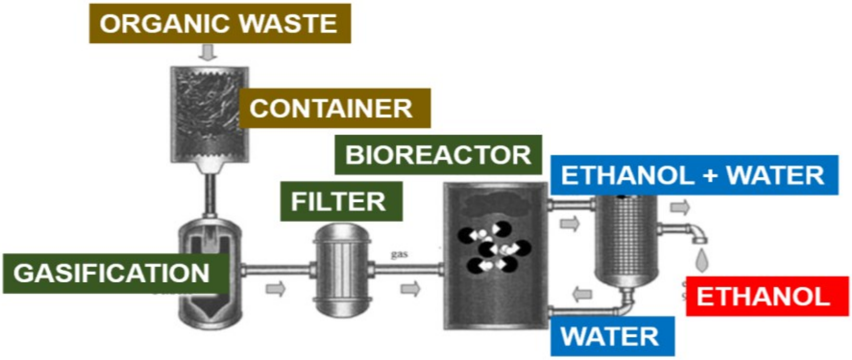

Fig. 4.1 Process of ethanol production from waste - schematic

According to General Motors as the promoter, the production costs of ethanol under this process remain below one US dollar per gallon (1US gallon = 3.785 liters) – and thus about half of the production costs for gasoline. To produce one gallon of ethanol by this process, one gallon of water is necessary, which is one third of the amount of water required in the production of conventional biofuels.

But the absolute hit for combustion engines will be methanol! People are currently talking about **"eFuels"** everywhere. These are, however, alcohols, obtained with the participation of renewable electrical energy from photovoltaic and wind power plants (hence "eFuels" or "electro-fuels").

The eFuels are alcohols made from carbon dioxide and green hydrogen. By recycling carbon dioxide between industry, heat engines and the atmosphere, they could save the existence of all internal combustion engines currently operating in the world!

With the "green electricity" of photovoltaic and wind power plants beside carbon dioxide-emitting industrial plants, hydrogen is produced from water as part of electrolysis. However, the main component on the way to the eFuel is another: the carbon dioxide pumped out of the nearby steel mill or coal-fired power plant!

Due to its economic and industrial performance, the Federal Republic of Germany has the highest carbon dioxide emissions compared to all European countries: 800 million tons per year (2018). Of this, 300 million tons come from the energy sector, 133 million tons from heating systems in corporate buildings and apartments, 160 million tons from industry and 160 million tons from road transport (automobiles and trucks).

Converting this amount of carbon dioxide into fuel is an immense challenge, but also a unique opportunity for the global climate.

A German steel mill (ThyssenKrupp, Duisburg) produces 15 million tons of steel annually, emitting 8 million tons of CO_2 - 1% of the total German CO_2 emissions. Using a new process (Carbon2Chem, 2018), the carbon dioxide emitted by the steel mill is collected in filters, stored and then converted into methanol by synthesis with hydrogen. For this purpose, the hydrogen is produced electrolytically right next to the plant, by means of its own, decentralized wind turbines [2].

The exhaust gas from the steel mill is sucked into a storage vessel, the contained carbon dioxide is separated by an alkaline filter at 80°C-120°C, after which the filter is cooled and the gas is led to a container. This process is cyclical. The carbon dioxide is directed from the container to a chemical plant and led with a hydrogen flow via catalysts to a synthesis reaction, resulting in methanol and water (Fig. 4.2).

The Carbon2Chem program stipulates the future conversion of 20 million tons of CO_2 per year. A similar plant was recently started up in Iceland. There, around 4,000 tons of methanol are produced from 6,000 tons of CO_2, with hydrogen production using environmentally friendly electrolysis.

The methanol produced in this way has recently been used as a fuel in large marine diesel engines.

Wärtsilä, one of the world's largest marine engine manufacturers, already produces novel four-stroke diesel engines with methanol direct injection. Another world-renowned diesel engine manufacturer, MAN, has developed a two-stroke engine with high-pressure direct injection of methanol. Both types of engines differ fundamentally from classic diesel engines in terms of mixture formation and combustion processes. The advantage of methanol as a fuel in diesel engines is not only the recycling of carbon dioxide, but also the considerable reduction of nitrogen oxide emissions, below the legal limit and the complete elimination of particulate emissions.

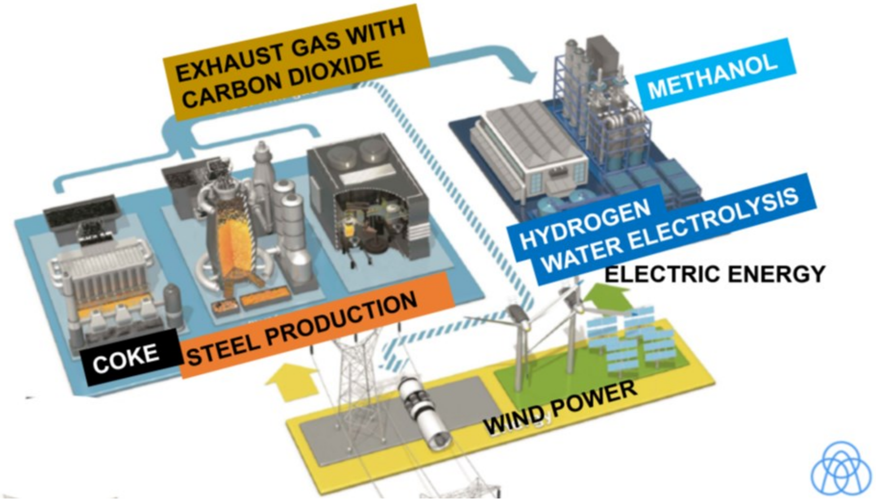

Fig. 4.2 Plant for the synthesis of carbon dioxide from industrial exhaust gases and hydrogen produced by electrolysis on-site (Sources: Federal Ministry of Education and Research, Thyssenkrupp)

In such diesel engines, methanol is injected directly into the combustion chamber as the main fuel and lit as a "pilot fuel" with the help of a small amount of biodiesel (Fig. 4.3).

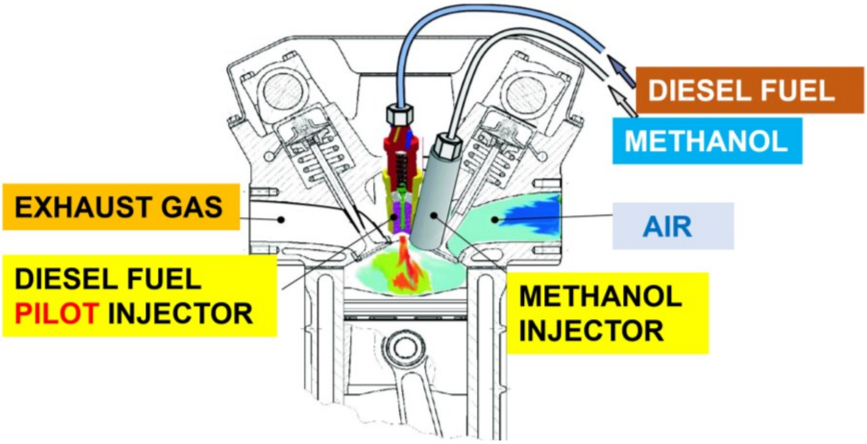

Fig. 4.3 Diesel four-stroke engine with main injection of methanol and pilot injection of diesel fuel

On the other hand, gasoline engines with methanol intake manifold injection, in China, are used on a large scale: 80% of the 10,000 taxis in the metropolis of Xi'an run on 100% methanol, which is a convincing argument – they would only build a Thyssen Krupp steel foundry on the outskirts of the city [3].

Siemens and Porsche, together with other partners, are building an eFuel plant in Patagonia, Chile, which will already produce 130,000 liters in 2022. Four years later, it will be 550 million liters. The price per liter in 2026 will be about 1.60 euros per liter, from 2030 the price could be one euro per liter.

Properties

Methanol and ethanol have lower calorific values than gasoline because they contain oxygen in their molecules. On the other hand, it is precisely because of this own oxygen that there is a lower demand for oxygen from the ambient air.

Conclusion: From one kilogram of air-ethanol mixture you get practically the same heat as from a kilogram of air-gasoline mixture.

Combustion

Conversions from automobile gasoline engines to methanol and ethanol already were made in the seventies, being extremely successful!

For example, Porsche used two fuel pumps instead of one when switching from gasoline to a mixture of 85% methanol and 15% gasoline, as well as injection nozzles with increased throughput and methanol-resistant materials for all fuel-carrying components. In addition, there was an adaptable engine management and an adequate engine oil. The torque of each such motor at full load was more than 10% higher at each speed and the efficiency increased in the same order of magnitude.

All car manufacturers that have tested or introduced this technology in series-production engines have achieved a torque increase of 10% to 15% when switching from 100% gasoline to 100% ethanol. The reason lies in the better and faster evaporation of the ethanol and in the effect of the oxygen content directly in the molecule during combustion. Due to the lower calorific value of ethanol compared to gasoline, for a chemically complete reaction, 1 liter of gasoline has to be replaced by 1.6 liters of ethanol. This has only to do with the chemically exact balance, but not with the efficiency of the combustion process. [3].

Perspectives

There were already over 50 million Flex Fuel vehicles worldwide in 2017: of which, as already mentioned, over 29 million in Brazil and over 18 million in the USA, followed by Canada with 600,000 and Sweden with 230,000 vehicles. Flex Fuel cars are built in Brazil by well-known manufacturers such as VW (about 50,000 cars per year), FIAT and GM (on the same scale), Ford, Renault, Toyota and Honda.

In the USA, around 216,000 Flex Fuel vehicles were produced in 1998, in 2012 more than 10 times the number (2.47 million), the current figure of 15.11 million proves beyond the respective government programs also the acceptance of this concept among customers [3].

In the longer term, the use of alcohols without gasoline content appears just as environmentally friendly as the use of electrolytically obtained hydrogen.

The main energy source and process concatenation are similar, only the energy-carrying component is different:

- Following the one path, the energy of solar radiation is used for propulsion by means of carbon dioxide, which is formed in combustion and split again **in a plant, as a natural reactor (photosynthesis)**. Thus, the carbon dioxide in the nature is used as a carrier of energy conversion.
- Following the other path, the energy of solar radiation is used for propulsion by means of *water,* which is formed during combustion and split again **in an industrial plant (electrolysis)**. In this case, the **water in nature** is utilized instead of **carbon dioxide in nature** as a carrier of energy conversion.

The only but essential difference between the two circuits is the cleavage of the respective molecule (carbon dioxide, or water). The cleavage plant for carbon dioxide is provided by nature itself.

4.4 Hydrogen

Production

Hydrogen production is ideally possible on the basis of solar energy or of the wind energy: you only need water and sun or water and a wind turbine. By means of electrolysis, with electricity from the sun or from the wind, the water is split in photovoltaic units into its two components, hydrogen and oxygen. Currently, however, only 2% of hydrogen is made in this way worldwide, the "remaining" 98% being produced from natural gas, heavy fuel oil and gasoline, thus, generating carbon dioxide as well!

The utilization of hydrogen, either by combustion in a heat engine or by proton exchange and thus generating electricity in a fuel cell, leads back to the original water.

Nevertheless, a considerable problem consists in the storage of the produced hydrogen. Every gas in nature is characterized by a gas constant, which determines the ratios between pressure, density and temperature in a certain state of the respective gas. However, the molecule of hydrogen is the lightest of all the elements of nature, making its gas constant the largest one. This results in the following problem: In order to achieve enough density of hydrogen in a storage tank, either the pressure must be set very high, or the temperature must be extremely low. Under frequently prevailing environmental conditions (pressure: 1 bar, temperature 20°C), an 80-liter storage tank would contain just 6.6 grams of hydrogen!

Air has a density about 15 times higher than hydrogen. As a result, in the same storage tank at same pressure and temperature air would have a mass of 100 grams. And what about liquid gasoline? Because of its density of 0.75 kilograms per liter, the same storage tank would contain 60 kilograms of gasoline! The calorific value of hydrogen (heat from the combustion of one kilogram of the respective fuel) is, certainly, three times as high as that of gasoline. As a substitute for 60 kilograms of gasoline, 20 kilograms of hydrogen would be necessary. But what can you achieve with 6.6 grams of hydrogen?

This physical condition inevitably leads to the storage of hydrogen either in the liquid state, at minus 253 °C or as a gas at high pressure, from 600 to 900 bar.

Such relationship remains independent of technical progress in the storage of hydrogen.

Combustion

Hydrogen is extremely flammable at a concentration in the air ranging from 4% vol. to 77% vol. The speed of the flame front is much higher than with other fuels. The flame is also invisible.

However, the air requirement is very high compared to that of gasoline or ethanol. This makes up for the great advantage of hydrogen in terms of calorific value per kilogram, as already mentioned. The combustion of a certain amount of a mixture of hydrogen and air does not bring more heat than the combustion of the same amount of a mixture of gasoline and air or of ethanol and air, it results rather less heat.

Storage is associated with another special feature: using cryogenic *(i.e. at extremely low temperature)* hydrogen filling, the entire storage and injection system, from the tank and pipes to the injection nozzles, must be thermally insulated to avoid a phase change from liquid to gas.

Injection into a combustion chamber is another problem. When hydrogen is injected into a combustion chamber, the following special features must be considered:

- The higher air requirement of hydrogen compared to gasoline, diesel fuel, methanol or ethanol means that the amount of air trapped in a combustion chamber requires less hydrogen mass, but much more hydrogen volume due to its low density. This requires either more injection pressure or a longer injection time, if possible.
- The contact of the injection nozzle with the combustion chamber demands its special thermal insulation. The jacket of the nozzle body has temperatures around 200 °C in many applications, but the hydrogen has minus 253 °C in the storage tank. At the nozzle, the liquid phase changes into a gaseous phase, which makes the density of the hydrogen at the injection point

very low. In order to inject a certain mass, the volume must become much larger. This requires either more nozzles, or more time, or both.

Perspectives

The first hydrogen car was already running at BMW in 1979, with a 4-cylinder engine that reached an output of 60 kW. Parallel to the development of hydrogen cars, BMW has been working on partnerships to produce hydrogen using solar energy and water electrolysis. In the car, the utilization of hydrogen facilitates the concomitant filling of the propulsion engine and of a fuel cell for electric power generation on board. BMW used for this purpose a compact fuel cell with an electrical output of 5 kW at a voltage of 42 volts.

As shown, amongst others, in this application of BMW hydrogen can not only be burned in combustion chambers of engines, but also used without burning, for the generation of electrical energy in fuel cells. A comparison of the reactions in the fuel cell with combustion is highly recommended at this point, even without far-reaching details about fuel cell designs and areas of application such as fuel cell cars.

The principle of the fuel cell dates back to 1839. However, their development was not pursued further at first. The breakthrough of the fuel cell based on pure hydrogen-oxygen flows over light catalyst electrodes in alkaline-aqueous electrolytes was achieved in the fifties, driven by special requirements for power generation in rockets for space travel.

The flows of hydrogen and oxygen are separated in a fuel cell by an electrolyte which, in conjunction with a catalyst, causes a proton exchange from the hydrogen flow (anode) to the oxygen flow (cathode) (Fig. 4.4).

In the fuel cells for automotive applications, the oxygen is obtained from the aspirated surrounding air, whereas the hydrogen is supplied from tanks on-board, which are pressurized at 600 to 900 bar or built as cryogenic systems for hydrogen temperatures of minus 253°C. Instead of an electrolyte the separation between the air and the hydrogen flow is ensured by a polymer membrane.

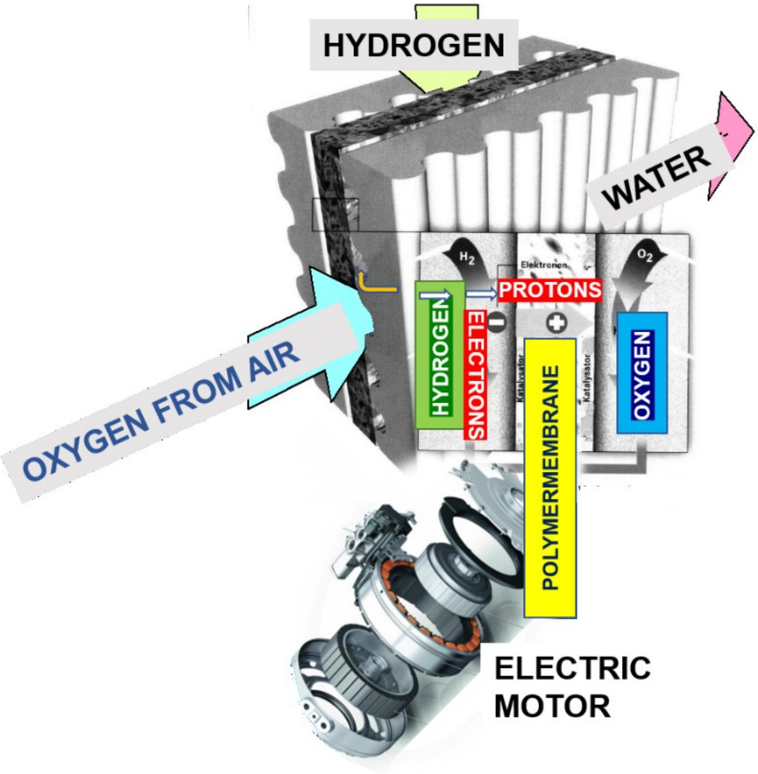

Fig. 4.4 Energy conversion in a fuel cell

Similarly, to combustion in heat engines, in a fuel cell not only the reaction of hydrogen with oxygen from the air is possible. Instead of hydrogen, a hydrocarbon (gasoline, diesel fuel) or an alcohol (methanol, ethanol) can also be used.

From this point on, a direct comparison of the reactions and processes in the combustion chamber of a heat engine or along the membrane of a fuel cell is not only possible, but also revealing.

Efficient combustion requires a very strong turbulence of the mixture of air and fuel. In a fuel cell, at first glance there are better conditions for a controllable process of the energy conversion: The reactants (hydrogen and oxygen) are basically separated from each other, which allows a better design and control of their mass flows along the membrane. In principle, both reactants flow in the same direction, simplifying the control of the reaction. However, the reaction surface must be increased when the fuel cell power requirement increases. This is much more advantageous during the burning process in a combustion chamber: The turbulence of the mixture in the combustion chamber greatly increases the contact area between the reaction partners hydrogen and oxygen. In addition, they are also in direct contact, without a membrane in between.

The main difference, however, is the temperature: In a fuel cell, the reactions usually run at 80 °C - 100 °C. whereas a combustion process achieves temperatures of 1600 °C – 2000 °C. As previously mentioned, the temperature is a pointer of the internal energy of the molecules involved. And these literally explode during a burning event, wherefore the splinters find their partners much faster.

Combustion remains the mother of all chemical reactions!

4.5 Vegetable oils

One of the most important sources of light for people for thousands of years was the fire from the oil lamp. At first, they were stone bowls, filled with animal fat and provided with a wick made of plant fibers and later of fabric residues. Over time, the animal fat was replaced by vegetable oils, the stone bowls used until then were then made of clay and metal and then protected from wind, rain or dirt with a lid, later with a glass lamp cylinder.

Production

Oils as fuels can be obtained from a variety of plants. This includes *rapeseed, beets, sunflowers, flax* in temperate climate zones and *olive trees, oil palms, coconut palms, peanuts, soybean, castor, cocoa and even cotton* in tropical or hot climates.

The extraction of vegetable oils by means of mechanical presses is widespread and relatively uncomplicated. In general, a stepped refining of these oils is carried out to remove fat accompanying substances that would be disruptive when the oils are used. Subsequent degumming removes phosphatides as well as mucus and turbidity. In the following deacidification, free fatty acids are removed, which have a corrosive effect against metallic surfaces.

One of the oils properties, the viscosity, makes their use, if obtained in the classic form considerably more difficult: The long-branched oil molecules that lead to this viscosity impair combustion in particular, because during this process the oxygen molecules can hardly reach the carbon. Coking on injection nozzles (Fig. 4.5) and combustion chamber walls are unavoidable in such cases.

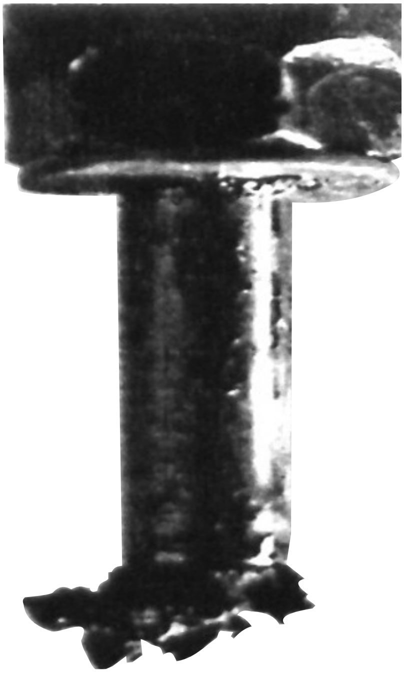

Fig. 4.5 Coking of the injection nozzle of a diesel engine with direct injection when operating with freshly pressed rapeseed oil

A fundamental solution to this problem is to shorten the branched oil molecules. The process is known as "transesterification".

The transesterification takes place as a chemical reaction of the oil with methanol, from which a methyl ester of the respective oil and glycerin are formed [3]. As a result, the viscosity is reduced by a whole order of magnitude and thus almost reaches the viscosity values of diesel fuels.

However, the process engineering for transesterification is considerable: The costs per liter of ester are comparable to the price of a liter of freshly pressed oil or a liter of diesel fuel.

1st generation biofuels

Such a fuel, which is produced in Germany from 80% rapeseed oil and 20% soybean oil, is known as FAME (fatty acid methyl ester).

2nd generation biofuels: Biomass-to-Liquid (BtL), Next-Generation Biomass-to-Liquid (NexBtL)

Such fuels are mainly produced from biomass - wood waste, straw, vegetable waste and from plant residues when the fruit is used as food.

The production is carried out according to the Carbo-V/Fischer-Tropsch process, by hydrogenation or by pyrolysis:

- Carbo-V/Fischer-Tropsch process (BtL, SunDiesel): The biomass is gasified in a reactor with the supply of heat and at a given pressure with the participation of oxygen. The process consists of three stages [3]. The energy content per cultivated area is about three times as large as when obtaining a first-generation biodiesel from rapeseed. With an average consumption of around 6 liters per hundred kilometers, an automobile with a modern diesel engine can cover more than 64,000 kilometers with the amount of SunDiesel obtained from one hectare of cultivated land.
- Hydrogenation process (NexBtL): A vegetable oil is mixed with phosphoric acid and caustic soda in a temperature range around 350 ° C and at a pressure of 80 bar with hydrogen (hydrogenated). Such a hydrogenation process can be realized in a classic refinery, the resulting fuel, as according to the Fischer-Tropsch process, does not differ from a conventional diesel fuel.
- Pyrolysis process: The biomass is heated to 475°C under exclusion of oxygen. The pyrolysis products are condensed as a result of the subsequent cooling. The calorific value corresponds to about half that of a conventional diesel fuel.

Combustion

In general, the performance and consumption behavior when using a freshly pressed oil, for example rapeseed oil, in diesel engines is comparable to that when using conventional diesel fuel. This is especially valid for large-volume engines. Operation with an ester, such as rapeseed oil methyl ester (RME), is recommended for automotive diesel engines.

The alternative of adding fresh vegetable oils to petroleum in a classic refinery process seems to be feasible as well. The resulting molecular structure is practically no different from that of diesel fuel.

4.6 Synthetic fuels

Synfuel or “designer fuel” is increasingly becoming the expression of a new trend in the development of energy carriers whose molecular structure can be specifically constructed.

The following criteria are decisive for the design of a synthetic fuel [3]:

- The extraction from renewable, inexhaustible resources in nature, such as plants that are not suitable for food, as well as from garbage of wood, plants, food or from the corresponding processing industry, through efficient recycling logistics.
- The extraction from the carbon dioxide emitted by combustion plants in industrial and power plants.
- The processing with low energy and process engineering effort, thus at low costs, mainly with electrical energy from wind and photovoltaic plants on site.
- The design of the properties according to the requirements of the machine in which the combustion is to take place.
- The reaction to end products that are environmentally friendly.

Combustion reactions with heat dissipation can generally be initiated from molecular structures of the carbon-hydrogen-oxygen type. The following applies:

- The ratio of the elements carbon-hydrogen in the molecule of such a fuel should be designed as far as possible in the direction of the maximum hydrogen content. This would produce more water and less carbon dioxide as a result of combustion.

- Where carbon is present in the molecule of the fuel, oxygen atoms should preferably be bound to the carbon atoms in order to allow rapid and complete combustion of the carbon. Often the oxygen from the air does not find its way or place to the carbon atoms in a strongly branched molecule. The generally leads to incomplete combustion and thus to soot or particle emissions.
- The molecular structure should lead to a liquid phase with the highest possible density in the range of gasoline or diesel density at normal ambient temperatures and pressures.

Of all the non-synthetic fuels listed so far, methanol and ethanol best meet these criteria. Recycling the resulting carbon dioxide in nature, without further effort, increases their value as alternative fuels.

Synthetic fuels according to the listed criteria are currently produced mainly by the synthesis of carbon dioxide and hydrogen with the intermediate methanol. These are polyoxymethylene dimethyl ethers (OME) with different chain lengths of the molecules.

As with methanol or ethanol, the oxygen in the molecule of an OME fuel causes the reduction in air demand from the environment compared to gasoline or diesel fuel. In a combustion engine with a given displacement volume, therefore, when the air requirement is reduced, the amount of the respective fuel injected must increase for reasons of chemical balance. In such a case, the increase in the amount of fuel injected has nothing to do with additional fuel consumption as a result of poorer combustion!

For some applications, such as in power plants or turbomachinery, however, there are also other interesting possibilities for designing fuels. These are metal powders and their mixtures.

The combustion of aluminum powder at very high temperatures is known from welding technology. The ignition of magnesium in the air from 500 °C has long prevented the pouring of magnesium parts. But as a powder, injected into combustion chambers, its use becomes an advantage. Iron powder reacts similarly with the oxygen in the air.

Mixtures of such solid fuels, in particular proportions of aluminum powder, are used in modern rocket technology due to their excellent energy density.

The design of metal powders in defined proportions of the components is less complex than in the case of synthetic liquid fuels.

And so, after about a thousand years, people come back to black powder: this time, however, finely atomized into the air, evenly distributed and only then, very precisely controlled, burned.

5

Fire causes emissions

5.1 Carbon dioxide

Fire has become a monster for our earth! Wood, coal, lamp oil, gasoline, diesel, natural gas, LPG, all contain carbon, and most of them hydrogen as well. When burning with oxygen from the air, carbon dioxide and water are produced in the best case. If they do not burn well because the carbon grains, the wood chips or the fuel droplets are too large, the carbon reacting with oxygen results not only in carbon dioxide, but partially in carbon monoxide and sometimes also in particles or soot [1]. The best combustion is given when the carbon contained in the fuel has been completely converted into carbon dioxide.

A magic fire in which the combustion of oil, coal or natural gas would produce no carbon dioxide at all, but only air or water, is a fairy tale for some adults without knowledge of physics.

The influence of the burning of fossil fuels on the Earth's atmosphere is currently regarded as an existential criterion for the heat-consuming economy.

Since the beginning of industrialization, after the invention and introduction of the steam engine (1712), the Earth's atmosphere has warmed by around 1 *°C*. It is noteworthy that at the same time the concentration of carbon dioxide in the Earth's atmosphere increased from 280 [*ppm*] (*parts per million - volume shares CO_2 per million parts of air*) to now 417 [ppm] [43]. However, the contribution of

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_5

carbon dioxide to the warming of the Earth's atmosphere is very controversial. The climate researchers of the IPCC (Intergovernmental Panel for Climate Change) consider the increase in the amount of anthropogenically generated carbon dioxide in the Earth's atmosphere to be responsible for the temperature increase at least during the last 5-6 decades. However, other scientists consider the changed intensity of solar radiation to be the cause of the rise in temperature and doubt the anthropogenic greenhouse effect.

Nevertheless, the predicted warming of the Earth's atmosphere at the current emission rate of 5.8 °C by the end of this century forces us to act quickly: The current goal of the international community is to slow down the warming of the Earth's atmosphere to 1.5 °C by the end of the century by drastically reducing man-made carbon dioxide emissions.

Is this really of vital importance for our planet, for its flora and for its fauna, including Homo sapiens? To understand the possible consequences of global warming, let's turn the problem around:

Was there perhaps life on our "twin planet" Venus, which has almost the same diameter (95%), almost the same weight (81%) and even an atmosphere?

The problem would be precisely this atmosphere: carbon dioxide is not represented in the millionths of a range, as in the Earth's atmosphere, but with a proud 96% of the volume of its atmosphere. We have 78% nitrogen in the Earth's atmosphere, on Venus it is only 3.5%. And what about the oxygen that humans and animals on Mother Earth need to breathe? The air of the Earth's atmosphere contains about 21% oxygen, on Venus there is no oxygen at all! However, there is 0.5% sulphur dioxide in Venus' atmosphere. In the air on earth we do not like such a component.

How does a “Venus atmosphere” dominated by carbon dioxide look? At first it is very dense, like a liquid. In connection with the absorbed solar radiation, the pressure at the bottom of the planet is not 1 bar, as on Earth, but 92 bar, as in a gasoline engine after ignition of the burning mixture of fuel and air. The temperature reaches 460°C on the ground, the gasoline would ignite there right in the tank itself.

All not suitable for the living beings we know on earth!

So back to Earth, first. The Earth's climate is determined by complex control mechanisms that are strongly coupled with each other. This mainly involves the biosphere, the oceans and the cryosphere (the ice masses). The main influences on the temperature of the atmosphere can be derived from a basic balance regardless of the complexity of the entire process:

The current average temperature of the Earth's atmosphere of around 15 °C is largely determined by atmospheric *water vapor* and trace gases such as *carbon dioxide, ozone, methane and nitrous oxide.* Such gases consist of molecules with 3 or more than 3 atoms, sometimes of 2 asymmetric atoms.

Without the natural greenhouse effect caused by water vapor and naturally present trace gases, the average temperature of the Earth's atmosphere would drop by 33 °C, i.e. to *minus* 18 °C.

The natural greenhouse effect can be explained in a simplified form in terms of the possible effects:

For its most part, solar radiation is emitted into the wavelength range of thermal radiation. Within this range is also the light radiation. The atmospheric gases with molecules of one or two symmetrical atoms are characterized by a far-reaching permeability for all wavelength ranges of electromagnetic radiation. Gases with molecules consisting of two asymmetrically located atoms and with 3 or more than 3 atoms, on the other hand, react selectively to electromagnetic radiation.

The high intensity of solar radiation to Earth is generally at short wavelengths, in the visible range, with small proportions in the ultraviolet and X-ray range. The radiation intensity at a given wavelength results in a heat flow that penetrates the atmosphere and further the bodies on Earth over their surfaces.

The proportional transfer of radiant energy to the bodies in the Earth's atmosphere in the form of internal energy causes a reduction in the intensity of the rays, which is accompanied by the increase in their wavelength. After transferring a heat flow to the body, the wavelength of the penetrated solar radiation changes from the visible range to the infrared range.

After a heat flow transfer, the solar radiation reflects from the earth. But the reflected rays have a changed, i.e. a "stretched" wavelength, after heat release. They are allowed to pass through the atmosphere unhindered by mono- and diatomic gases, but not by multi-atom gases, which push a significant part of the radiation back into the Earth's atmosphere (Fig. 5.1). This creates a heat flow again; the intensity and wavelength of the returned radiation are changed again. The internal energy and thus the temperature of the Earth's atmosphere and the warmed bodies on Earth thus increases to an energetic balance between reflected and absorbed radiation.

This natural greenhouse effect in the Earth's atmosphere is mainly caused by *water vapor, carbon dioxide and ozone.* Carbon dioxide is the second most important proportion.

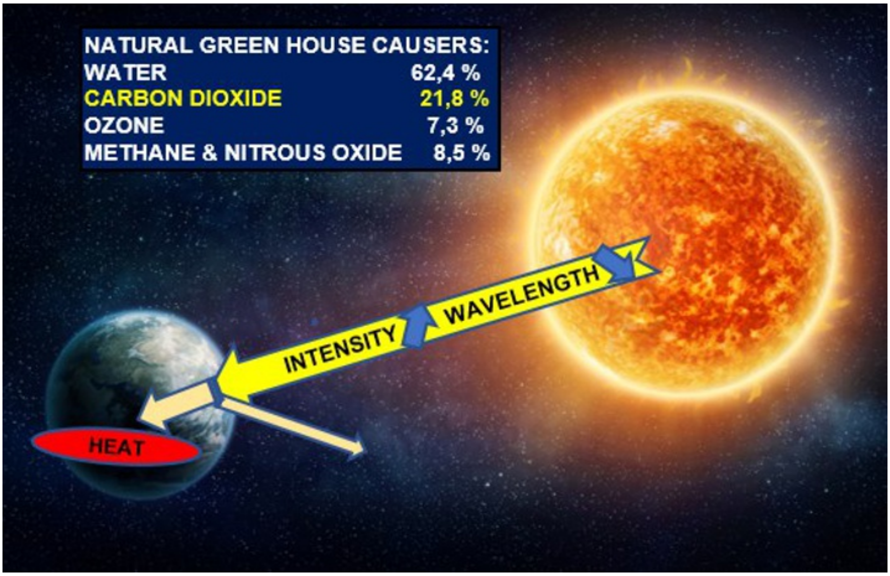

Fig. 5.1 Origin of the natural greenhouse effect in the Earth's atmosphere

In a classic greenhouse with glass panes over tomatoes and lettuce in the garden, it is not mainly the water vapor and carbon dioxide from the air that acts as a barrier for the reflected reflection of the sun, but the silicon dioxide of the glass panes.

The greenhouse effect is clear and pleasant to feel on a glazed veranda, on a frosty winter day with bright sun in the blue sky: outside *minus 20°C, inside plus 20°C. As soon as a window is opened, however, the greenhouse effect including plus degrees is gone, on the veranda then suddenly the frost is felt!*

And now comes the fire as a monster: Every combustion of a carbonaceous energy carrier basically produces carbon dioxide [1]. By burning fossil fuels such as *coal, petroleum products and natural gas,* carbon dioxide emissions exceed 20 billion tons per year, accounting for over 0.6% of natural emissions in a natural cycle. However, the latter takes place as a result of photosynthesis in a natural cycle [2].

The combustion of one kilogram of gasoline or diesel produces around 3.1 kilograms of carbon dioxide. Burning one kilogram of coal yields 3.7 kilograms of the same greenhouse gas, while burning one kilogram of natural gas results in only 2.7 kilograms of carbon dioxide.

Most climate researchers base their forecasts on cumulative carbon dioxide emissions in the atmosphere caused by anthropogenic combustion. In the past 50 years, by the way, the winter temperature in Europe has increased by 2.7 °C, a fact that supports such predictions.

However, critics of this scenario consider other natural factors, such as the variable *intensity of solar radiation* or the activity *of volcanoes,* to be decisive for global warming over the past 150 years. For these critics, the established model of the carbon dioxide cycle in the atmosphere, biosphere and hydrosphere is implausible. This also applies to properties of the absorption of CO_2 radiation and to the assumed CO_2 lifetime. Despite these concerns, a drastic reduction in anthropogenic carbon dioxide emissions, which are obviously growing too strongly, is being sought worldwide.

But where do these threatening carbon dioxide emissions arise? The answer is sobering and frightening at the same time:

70% of the world's carbon dioxide emissions are generated in cities!

4.5 of the totals of 7.9 billion people, i.e. 57% of the world's population, currently live in cities (mid-2021), and by 2030 it will be an estimated 5.2 billion. All this people need houses and heat!

The construction and building sectors account for 38% of global greenhouse gas emissions [44]. Cement production alone accounts for

8% of the world's CO_2 emissions, with only half caused by process heat, the other half by the chemical conversion of limestone to cement (calcium carbonate). Fire-intensive steel production is responsible for 10%.

And people also need warmth, at least the one generated by heating systems. Coal, wood, natural gas and heavy fuel oil are mainly burned centrally or decentral. The fire for heat and electricity causes over 40% of CO_2 emissions worldwide.

Transport, on earth, in the air and on water, with gasoline and diesel-swallowing internal combustion engines, is responsible for a quarter of global emissions. Trade, commerce and the service sector provide the rest [45].

Nevertheless, the fire is not a monster: because of the anthropogenic carbon dioxide emissions, neither the power plants nor the domestic heating systems nor the combustion engines have to be shut down. There are two other solutions of the problem, each one both rational and pragmatic:

From now on, the people of all countries should burn climate neutral fuels and couple the various processes in power plants, machines, heating systems and combustion engines according to the most effective rules of thermodynamics.

5.2 Nitrogen oxides

For the fauna and flora of the earth, *air* and *water* are existential elements. The fauna, from fish and insect to humans, also needs carbonaceous food in the form of hydrocarbons, proteins and fats. This food is generally secured by each other eating: not only human-potato, and insect-plant, but also human-fish, fish-fish, human-human.

But humans also need *warmth.* To this end, it fires wood, coal, natural gas and crude oil in furnaces and power plants. This results in carbon dioxide, which rises into the air to be breathed and heats the atmosphere. However, man also needs working machines and means of mobility, for which steam and heat engines as new carbon dioxide slingshots, were created in the course of industrialization.

And so, it goes on cheerfully: Humans also need energy for rockets, for bombs and for fuel cells, but also for chemical products. They even came up with the idea of splitting the water in order to get the hydrogen. Breaking the strong bond between the oxygen atom and its two smaller hydrogen brothers was dubbed “electrolysis" because it requires electrical energy. However, the electric energy is produced worldwide mainly by burning coal, oil and gas. In this way, carbon dioxide is blown into the air again, as if by fire.

And because it is about the cleavage of molecules into atoms: Humans have done this not only to water, but also to the air. This consists mainly of molecules of nitrogen (78%), formed from two nitrogen atoms and of molecules of oxygen (21%), formed from two oxygen atoms. The molecules of nitrogen and those of oxygen normally coexist in the air without interfering with each other: each of them with its own atoms. The big problem arises when *gas, alcohol, hydrogen or diesel fuel* is poured over the air to ignite a fire: fire for grandma's stove, fire for the steel cooker, fire for the pistons of the diesel engine.

For the firing of a fuel of the mentioned type, however, only the oxygen from the air is required. Does the nitrogen then remain inert, uninvolved in this event? For a while, it is so. But at some point, when the fire reaches temperatures above 2000°C, the two atoms of some nitrogen molecules begin to tremble so much that they are thrown out of their careers [1]. They then shoot back and forth, outside their mole-tulle mothers, between the similarly formed splinters of carbon (C), oxygen (O), nitrogen (N) or random bonds (CO, HC, OH) floating in the fire (Fig. 5.2).

According to Murphy's laws, what must not happen always happens: A free-floating nitrogen atom combines with a free-floating oxygen atom in a novel molecule: nitric oxide. Sometimes two oxygen atoms want to meet a nitrogen, they then form a stick dioxide. Or two to three and two to four. And so, the catastrophe of the modern world arises: the nitrogen oxides!

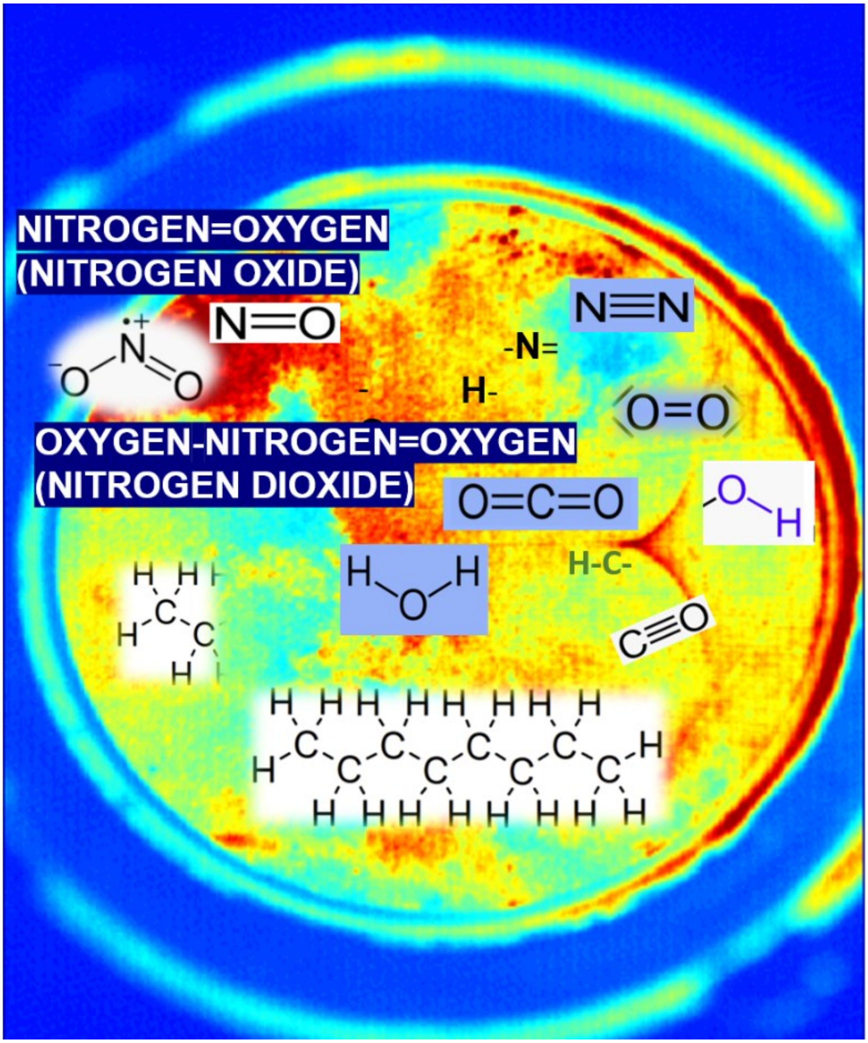

Fig. 5.2 Formation of new molecules from free-floating atoms during combustion in the combustion chamber of a diesel engine at temperatures above 2000°C

Is this really a catastrophe, is it a sign of the modern world? As if! From heaven, since the earth existed, lightnings has come naturally. They cut into the wood or into sheep, the wood was immediately charred, the sheep grilled just as quickly.

What is the difference between a flash and a flame?

The energy of a flame can be awaked by that of a flash concentrated in a beam, such as a laser beam. This lightning beam first drills through the air and, due to its temperature of 20,000-30,000°C, decomposes the molecules of oxygen and nitrogen into atoms, which then, chaotically or not, assemble into nitric oxide molecules.

In the Earth's atmosphere, 60 to 120 lightning bolts occur every minute, mostly over the Earth's surface. They cause twenty million tons of nitrogen oxides in the atmosphere every year by splitting the molecules of oxygen and nitrogen in the air. In the troposphere, i.e. at altitudes below 5 kilometers, nitrogen oxide emissions in the summer months achieve more than 20% of the total amount caused by industry, traffic and heating systems.

And where is the real problem? The nitrogen oxides (NO, NO_2 and other N, O bonds) penetrate the bronchi of living beings and occasionally cause their irritation. They then reach the tissue of the lungs in the further course of the airway, via the trachea, and can dampen the oxygen flow into the blood.

In a further context, the mixture of nitrogen oxides with water vapor in the atmosphere leads to the formation of acids, in particular nitric acid, which condense in raindrops (acid rain) and damage the trees in particular on the ground.

And now the automobiles come into play: Their combustion engines, it is generally reported, cause more than half of the nitrogen oxide emissions generated by humans in the Earth's atmosphere. The other half comes in particular from the energy sector of industry and heating systems in residential buildings. And among internal combustion engines, diesel is the main culprit. It is believed to have found the solution: the diesel will be eliminated, at least from the automobiles. Half of the fleet of European cars is to be replaced. What did people find so great about these diesels? The consumption, what else? A third less consumption for the same power is not negligible. And, in addition, the powerful torque from a standstill, which is indispensable for heavy sedans, trucks and tractors. Such advantages cannot simply be given out of hand.

Why does a diesel engine emit more nitrogen oxides than a petrol engine? Because the combustion proceeds differently [1]:

- A mixture of gasoline and air is whiped by lightning at over 4000°C produced by the spark plug. This lightning splits the molecules of air and gasoline around it. Splinters of it, whether broken hydrocarbon chains or individual carbon atoms, then increasingly hit oxygen splinters (atoms) from the air and combine with them. This compound causes heat, a lot of heat, which is then also transferred to the neighbors, who in turn burst into countless splinters. This process propagates like an avalanche, but a hot avalanche, into the entire combustion chamber above the piston.
- Within a diesel combustion chamber, the compression provided by the piston upwards movement makes the air hotter (on average 600°C) than in a gasoline engine (on average 400°C). Only towards the end of this compression the diesel fuel droplets are injected into the air and converted by the air heat into billions of small, burning islands. Admittedly, the temperature of the compressed air in the diesel engine (600°C) is much lower than that of the flash (plasma) from the spark plug in a gasoline engine (4000°C), which also slows down combustion. However, the diesel islands all burn at the same time, while the drops of gasoline only gradually burn in a continuous front through heat transfer from neighbor to neighbor. The diesel islands combustion, slower but concomitant, leads to two effects: The entire combustion process is longer and has a higher temperature than in the gasoline engine. The higher temperature leads to a higher efficiency and thus to a lower fuel consumption with the same heat. The bad thing is that at a higher combustion temperature and at a longer combustion duration, some nitrogen and oxygen molecules burst in the air in the combustion chamber that was not involved in the actual combustion. And so, according to Murphy's laws, there are splinters that should not come together: oxygen and nitrogen atoms that in coincidence form nitrogen oxides. How can be that avoided? By lower compression? Why not, this is partly done by engineers who make it easy for themselves: in this manner, the nitrogen oxide decreases, but also the efficiency, which increases consumption. Is there another way? Certainly, with one absorbent catalytic converter after another, ever larger, heavier and more expensive

> or with a conversion of the nitrogen oxides in the exhaust by means of urea currents from an extra tank.

Do many filters and sophisticated modules in the chimney help more than a better control of the fire in the fireplace itself? Up to a certain emission limit, certainly. And then?

The next step is undoubtably to take better care of the combustion itself! The focusses with hot temperatures within the combustion chamber of a diesel engine, in which the nitrogen oxides are produced, are not homogeneous distributed, however, clearly localized. This can be determined by simulations and experiments. Some developers want to cool these focusses during combustion by introducing water or cooled, no longer reactive exhaust gas, into the combustion chamber. However, inhibiting combustion means reducing the efficiency of the process. Fortunately, there is also another way: the fuel can be injected in five, six or seven small portions per cycle, with well-controlled intervals between them, which means that local temperatures cannot rise excessively. This can also be combined with fuel pressure modulation. Will that be enough?

The nitrogen oxide emissions of diesel cars currently lead to dangerous concentrations in the air of large European metropolises. This will lead to a further, drastic reduction in emission limits. If the diesel engine with its advantageous torque curve and low consumption is to be saved, only a redesign of the combustion process itself will help, in conjunction with the use of new, regenerative fuels such as biogas or alcohols.

Isn't the air at the end of compression hot enough to make the fuel droplets burn faster than the nitrogen oxides can be produced? Then it should become hotter, but no longer by compression. A few drops of an additional, quickly flammable fuel create the first burning islands - like the small matches in the fireplace, before the large pieces of wood - in this case the many droplets of the main fuel are thrown in [1], [46]. This type of preheating of the combustion chamber creates miracles: the main fuel – biogas or alcohol – then burns more vividly, the pressure becomes noticeably higher, the burning time is significantly lower, there is no time left for the formation of nitrogen oxides, which is reflected in a rather dwindling concentration. Admittedly, the quickly flammable initial fuel needs its own, albeit small, tank – but this is currently similar with AdBlue for the catalytic converter, which can then be eliminated.

5.3 The particles

The particles are always a thorn in the side of environmental organizations and climate protectors when it comes to vehicles with internal combustion engines. Their like to see the particles resulting from fuel burning in heat engines, but not the rest of the dust from billions of particles that bombard us from many sources. Admittedly, very small particles are not always visible: the human eye cannot perceive particles with a diameter of less than 50 microns, which pass through the cornea of our eyes along with the four billion photons that bring us light every millionth of a second. That's not good. Equally bad is that these particles pass through our nose, then the throat, larynx, trachea, bronchi and bronchioles, to the alveoli to enter our blood.

The particles resulting from the combustion of a fuel, in the stove or fireplace at home, in the industrial and power plant fireboxes and in internal combustion engines of vehicles, contain unburned or incompletely burned cores of carbon or hydrocarbons.

However, combustion is not solely responsible for particle emissions. There are also other equally dangerous sources of particles. The most important of these are the following:

- The dust that is stirred up on fields and dirt roads. This dust contains both organic and inorganic particles. On the asphalted roads, splinters of hydrocarbons jump from the bitumen portions as polycyclic aromatics that are carcinogenic. But there are as well small stones of various minerals.
- The particles that are torn off and ejected by the abrasion from the tires of all vehicles, including those of electric cars, during contact with the road surface. In Germany, this is about the same amount as that of the exhaust gases of all combustion engines. In addition, there is the abrasion of clutches and especially of the brakes. It results the same number of fine particles as from the tires or as from the exhaust gases of the combustion engines.

- The particles produced by trams in a city by braking sand and abrasion of the wheels on the metal rails: In Vienna, for example, trams emit about 417 tons of particles with diameters of 10 micrometers from ground brake sand and 65 tons from wheel abrasion every year. Ground quartz sand is considered highly carcinogenic.

Inhomogeneous mixtures of solid and/or liquid, extremely small particles suspended in any gas are commonly referred to as "aerosols". For particles of the described type that float in the atmospheric air, the term "Particulate Matter" (abbreviation: PM) was also introduced internationally. They are divided into size classes: PM 10 are, for example, the particles with an average diameter of 10 micrometers (one hundredth of a millimeter).

The dust with particle sizes of more than 10 micrometers, which humans very often get blown into their faces, is largely braked in the nose and enveloped in an endogenous secretion with higher viscosity, in order to then, usually be excreted in a handkerchief (Fig. 5.3) [47].

Particle sizes below 10 microns, till a size of about 2.5 microns, can pass through the nasal mucus and get into the bronchi. Falling below this particle size, they can reach the alveoli. However, the more acute problem is caused by the inhaled particles with sizes below 0.1 microns, which can get into the blood vessels. The approximately 300 million spherical alveoli in a person's lungs have a total area of 80 to 120 square meters, which is 50 times more than the average skin area of same person! Through the surfaces of the alveoli, the gas transfer is realized, which ensures the function of the organism: The inhaled fresh air contains about 21% vol. oxygen which is passed into the blood. On the other hand, the carbon dioxide resulting from the energy conversion in the cells is transferred from the blood to the lungs and exhaled from there.

When fine particles enter with the inhaled air into the alveoli, they cause inflammation of the surfaces or water retention. It is worth noting that even inhaled water droplets with sizes around 0.1 to 2.5 microns act as particles!

The distribution of dust and particles in Europe, using the example of particles with an average size of 10 microns, shows very strong differences, especially between Scandinavia (less than 20 micrograms per cubic meter) and Central Europe or northern Italy (where more than three times the amount was repeatedly measured!).

In Germany, there were no less than 59 million motor vehicles and around 8 million vehicle trailers in January 2021 (mentioned here because of tire abrasion) [48]. The fine particle emission is obviously largely due to road vehicles, although the shares of the industry, the energy sector and domestic heat generation reach a similar magnitude. The proportion of vehicle emissions is higher the finer the particles are. The main culprit is the combustion in piston engines.

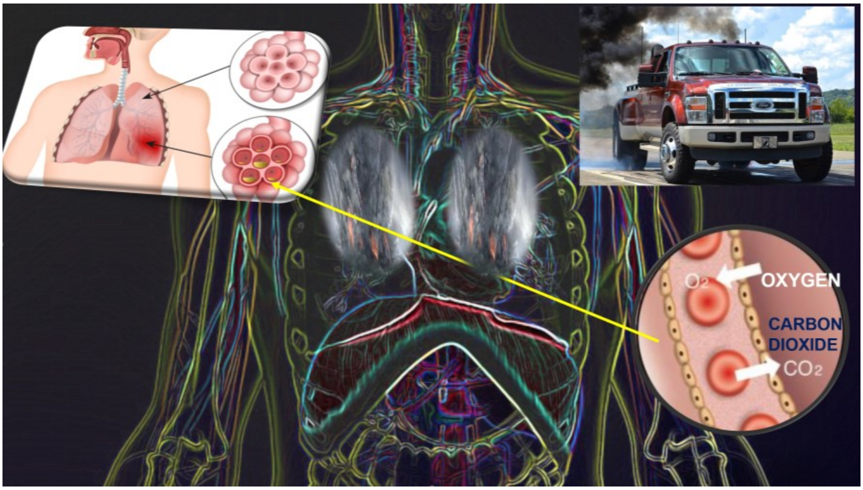

Fig. 5.3 Particle pathways through the nose, bronchi and alveoli into the blood

For the most complete and efficient combustion of the hydrocarbons contained in a fuel, the injection jet into the combustion chamber of a thermal engine must be atomized in very small droplets. However, the time available for atomization and further mixing of these droplets with air is extremely short, about half a thousandth of a second. This causes liquid cores of the tiny droplets which do not burn, or do not burn completely. These cores have diameters in the order of 0.1 micrometers and are then ejected from the combustion chamber with the exhaust gases. Would it also be possible to burn these droplets? Increasing the injection pressure, the jet atomization becomes very fine. On the other hand, injecting the fuel in small portions there is more air around the droplets. Thus, the combustion becomes more efficient, fact which is demonstrated by the increased flame temperature. But that brings us back to the bursting of the molecules and so to the nitric oxide. This is the biggest dilemma for combustion engine developers: applying measures to reduce the nitrogen oxides emission, both the fuel consumption and the particle emission increase, and vice versa. Gist: flame temperature high, particles down, consumption also, but nitrogen oxide high.

Wouldn't it be better to leave the injected drops a little larger, i.e. to atomize less, as with the old, classic in-line diesel fuel injection pumps? Admittedly, in this case soot is produced, which are unburned hydrocarbon cores, being only slightly roasted on their surfaces. But this soot is highly carcinogenic!

A solution which is equally applicable for diesel and gasoline engines with direct injection consist on the controlled, simultaneous combustion in numerous mixture cluster. The dilemma of particles against nitric oxide as variables on a hyperbola remains basically preserved, but the mentioned type of combustion pulls this hyperbola downwards. The results so far are encouraging.

But don’t blame combustion per se for the particulate emissions of vehicles! The biggest problem of particle emissions from future automobiles, although they will be electrically powered by motors with batteries, fuel cells, or even heat engines, remains the tires! Of the 205 thousand tons of fine particles that are currently emitted in Germany per year, 42 thousand are due to road vehicles. On the other hand, 6 thousand tons of them are caused by friction of the tires on the road and 7 thousand tons by friction in the brakes. The particles dropped by the tires contain zinc and cadmium, those from the brakes nickel, chromium and copper. The wheels of the train and tram cars lead to abrasion and shedding of fine iron particles in contact with the metal rails. Admittedly, humans, as well as living beings in general, have calcium and magnesium in bones and brain, phosphorus in the bones, iron in the enzymes. But too much of all them is either not healthy.

A mid-range automobile emits an average of 39.9 grams of rubber particles per hundred kilometers due to the friction of its four tires on the road, of which 0.15 grams have a diameter of less than 10 micrometers. These values were measured and processed using statistical methods, considering the variety of tire types and road surfaces. A simple experiment in this regard can be carried out in your own garage by weighing a tire in its new state and then after ten thousand kilometers of driving. The result will be surprising indeed. The most dangerous aspect is that these rubber balls penetrate our lungs and those that remain on the road are eaten by millions of worms and other animals, which in turn can get into our salads, and thus also into our stomachs.

However, this is not a reason to panic: particles of this magnitude are usual for humans. A cholera particle is two micrometers long and half a micrometer thick, rapeseed and spruce pollen particles have about ten micrometers in diameter. And it can be also worse: laser printers are in our time usual in millions of offices. A laser-printed page leads to the emission of dust from two million very fine particles that enter the alveoli of the lungs via the nose and respiratory tract.

In London, in the year 2003 has been introduced a fee for the travel of vehicles through the city center. This has led to a traffic reduction by a third. Surprisingly, however, the particle emission in the City of London has remained absolutely unchanged.

The fuel burning in the internal combustion engines of the mentioned vehicles is therefore not the biggest culprit in terms of particle emissions in cities.

In heat engines, the fire is precisely controlled and controlled. But what about the volcanoes of the earth, in which the combustion is absolutely uncontrolled? These volcanoes emit no less than eighty million tons of ash into the air each year. The particles contained therein are mostly smaller than five microns. And such particles penetrate into the lungs.

Nevertheless, another burning form is even more dangerous in terms of particle emission than that of the volcanoes: the burning without fire, more precisely the glow of the coal or wood pieces in an industrial or campfire or that of pipes, cigars and cigarettes of any kind! This is most clearly revealed by the color of a smoker's alveoli. The particles in the cigarette smoke have, as an example, sizes between 0.1 and 1 micron. They enter the bloodstream and "enrich" the blood cells with carbon monoxide, benzene, formaldehyde and other delicacies.

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Part II

Thermodynamics of fire

6

Heat and work change states

6.1 Phenomenological consideration of state changes

Thermodynamics is a combination of words of the ancient Greek terms "thermo" (warm) and "dynamis" (force). It shows that heat and work are closely linked. This has been the subject of general physics for centuries. After the development and spread of steam engines in the 18th century, the complexity of this interaction has increased significantly and so thermodynamics has become an independent science.

Modern "technical" thermodynamics deals with energy exchange, energy conversion and energy transfer in technical systems.

The forms of energy treated in thermodynamics are, according to the illustrations in Chapter 3.1: Heat, Work, Internal Energy and Enthalpy [1].

Heat and/or work only appear during a change of state (exchange, conversion, transfer of energy), but they are not present in a specific state.

Examples: heat from the human body at 37°C to ambient air at 1°C; work of a turbine when turning a shaft.

The energy that a system can store in a state consists neither of heat nor of work, but only of the energy forms internal energy and enthalpy.

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_6

Examples: Internal energy of the exhaust gas in a currently closed combustion chamber, enthalpy of water vapor in a boiler, when flowing out to a turbine.

A system usually contains a medium that provides the exchange of heat and work or stores the internal energy, or the enthalpy (Fig. 6.1). In particular, the following are considered to be working media (called also working fluids):

- Gases and gas mixtures

Examples: air, hydrogen, exhaust gas mixtures

- Vapors

Example: water vapor

- Gas-steam mixtures

Examples: humide air, air-fuel mixture.

Solid working media usually are used during an energy transfer.

Examples: heat conduction through pipe walls, heat radiation from the tiled stove.

An exchange of energy between a system and its environment leads to a change of the thermodynamic properties of the working medium. Thermodynamic properties or state variables include *pressure, temperature and volume.*

Thermodynamics has its own laws, even if they were derived from the general laws of physics. A major reason for this is the large number of particles in a working medium.

The laws that apply to a medium as a whole are different from the laws that apply to parts of this medium.

Example: Air consists of particles of nitrogen (78%) and oxygen (21%), other gases remaining together at 1%, which is negligible in this context. The cylinder of an internal combustion engine with a volume of 0.5 liters contains at a pressure of 1 bar and at a temperature of 20°C not less than 7,521,681,200,000 billion particles of nitrogen and oxygen.

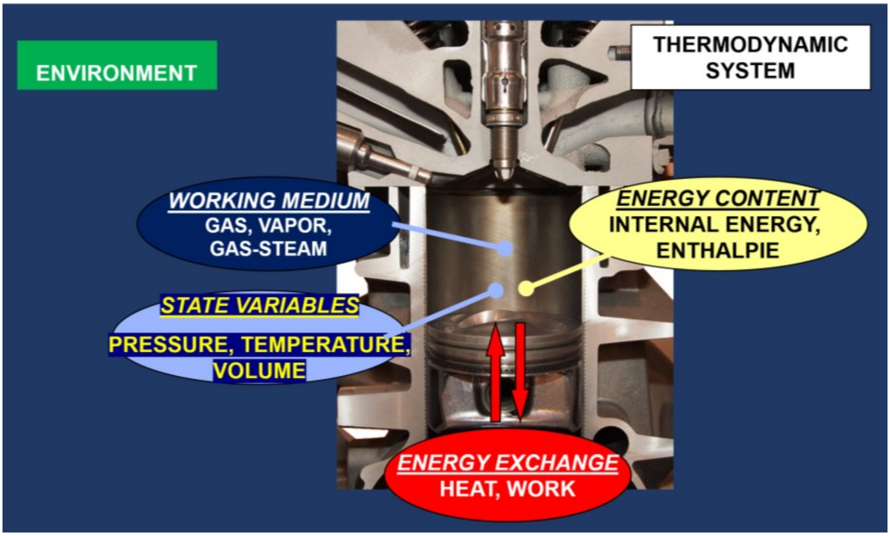

Fig. 6.1 Energy quantities, working media and system variables

Although the behavior of each particle determines the laws in the overall system, such single behavior is not sufficient for justifying a general law.

Example: For each particle of nitrogen or oxygen in a container filled with air, the property named temperature (Chapter 3.1) makes no sense. Each particle simply has its own kinetic energy. For the air as a whole, on a macroscopic scale, temperature is an agreed expression of the kinetic energy of the totality of the particles. This temperature can be measured with a thermometer attached to the container.

Such a difference between the behavior of individual system parts and that of the system as a whole requires own methods of investigation.

There is a choice between determinism, phenomenology and atomistic-statistical analysis.

Determinism, as an analytical investigation methodology – applicable to processes in physics or technical mechanics – is not suitable for the analysis or calculation of thermodynamic processes. Determinism can generally be applied to a limited, controllable number of material particles: For example, by determining the motion conditions of each particle at any moment and at any location, both the current and a later state of motion in the entire system can be determined.

Fig. 6.2 Balls and cues on a billiard table

Example: Hitting the ball on a pool table. (Fig. 6.2). You can adjust the impact force and the cue position knowing the position and weight of each ball and the table cover fabric so that the orange ball hits the blue one, this then the pink one, which meets the green tangentially, so that the latter enters the hole.

However, one should not necessarily apply this knowledge in the human world, and especially not in the formulation of laws:

Using deterministic methods, from the analysis of the behavior of a single individual, it is practically impossible to derive the behavioral characteristics of an entire society.

Nevertheless, this is often practiced in politics, economics and finance, with usually momentous results. Corresponding examples could fill an entire book.

Phenomenology is not completely analytical, but pragmatic: the macroscopic phenomena are considered in a medium, initially without reference to its microscopic structure. The boundary between the macroscopic and the microscopic structure corresponds to the range of effectiveness of an applicable law. Each property must still be measurable or detectable with senses up to such a limit according to its exact definition.

Examples: temperature, pressure, color, smell, taste, sound.

In a phenomenological investigation, all laws are determined experimentally (*"Phänomenon", from ancient Greek, means "appearing").* As a result, such laws are hypothesis-free.

Experimental, however, does not mean empirical, whereby a single, specific process is expressed in a mathematically tailored form.

Phenomenology can be defined as a summary of exclusively experimentally gained knowledge for as many similar processes as possible with subsequent derivation and formulation of laws and recording of such laws in short, concise formulas, if possible.

In the case of a phenomenologically derived law, however, a single experiment that contradicts the respective formulation is sufficient to invalidate the law in general, or a part of its sphere of action.

Example of a phenomenological law: "Heat can never pass by itself (naturally) from a body with a lower temperature to a body with higher temperature", Clausius (1822-1888), one of the formulations of the Second Law of Thermodynamics. So far, since the time of Professor Clausius, nothing has ever happened anywhere in the world that would contradict this law.

For each law that has been phenomenologically derived, however, the following criteria must be considered:

- Premises,
- Area of validity,
- Boundary conditions.

A certain disadvantage of the phenomenological method of investigation is that well-founded physical explanations of the experimentally gained experiences are not available through their macroscopic consideration and are not necessarily sought. However, as long as this method allows the simulation, extrapolation and reproducibility of processes in the development of systems or plants, such a compromise is justifiable indeed.

Example: The fire. The flames during the combustion of wood, coal, gas, gasoline or candle wax send warmth, colors, smells and sounds into their environment. All this can be detected externally not only with human senses, but also measurable with devices. A current state, as a combination of the same properties, can then also be restored by strictly adhering to the entry requirements. But it is of little use if one can analyze exactly why a particle of nitrogen or a small piece of coal travels from the blue to the red area of the flame and how its further path through the flame runs or would run. The main thing is to be able to reproduce everything in such a way that the second, the third and the thousandth times the blue zone appears exactly in the same place, and the temperature distribution in the flame is exactly the same. The physicist would be upset because with his knowledge and with modern computers, it would be possible to track the orbit of each particle among the many billions in the flame. However, he would work on such a task from his doctorate to retirement age, while the engineer could transfer his precisely working machine with such a combustion chamber into production in three months (Fig. 6.3).

Fig. 6.3 Flames from a coal fire and from a wax candle, with different shades, from blue and dark red to yellow, each signaling a temperature zone

The ***atomistic-statistical investigation methodology*** is an alternative to phenomenology, which is more likely to be used in the physical analysis of thermodynamic media or processes. The behavior of a medium is analyzed on a microscopic scale using deterministic methods. Statistical methods are used for the transition to macroscopic behavior. In this way, physical justifications for phenomenologically derived laws can also be found if necessary.

6.2 Heat, work, degrees of freedom of properties

The medium (usually *liquid or gaseous)* within a machine or plant can exchange *mass* and energy (*heat or work)* with its environment.

Numerous exchange combinations are possible.

Example: The medium which is enclosed within every piston engine is gaseous air, containing fuel droplets, vaporized from liquid to damp (gas). Igniting and burning the air/fuel mixture there appears energy in form of heat. Part of this heat is converted into mechanical work, given by the pressure of the burned gas mixture which pushes the piston on his course. This work is mechanically transmitted to the crank and then forwarded to the consumer, which can be an electric motor or a power gear. The rest of the heat within the cylinder, which was not used for pushing the piston, is partially transmitted through the cylinder to the cooling system of the engine and partially discharged into the environment as hot exhaust gas. Such a piston engine, as a machine with combined exchange of mass, work and heat is illustrated in (Fig. 6.4).

The instantaneous state of the working medium in a machine or plant, expressed by the values of state variables (properties) such as *pressure, temperature or volume,* can only be determined in a macroscopic equilibrium.

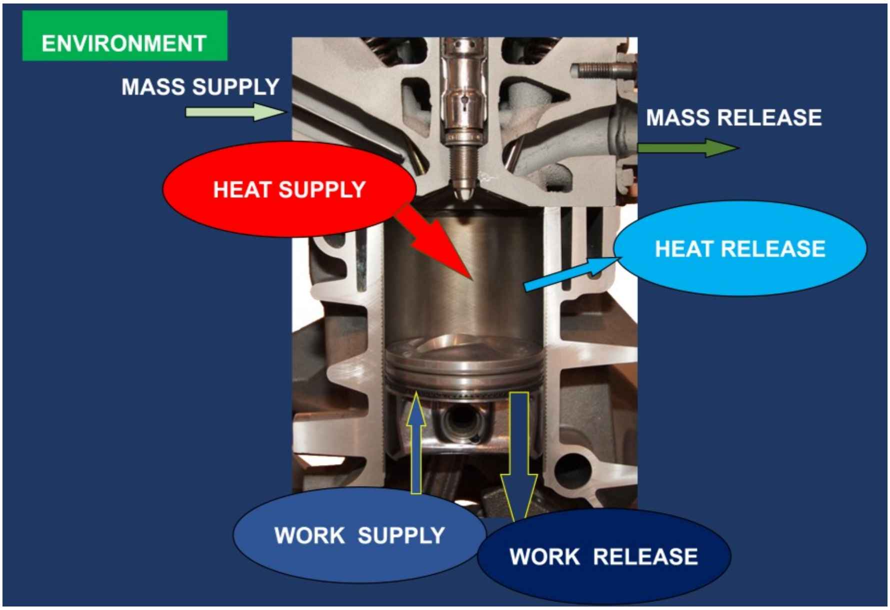

Fig. 6.4 Piston engine as a machine with combined exchange of mass, work and heat

On a microscopic scale, there is a constant movement of the particles; however, considering that this internal movement is in a dynamic equilibrium, its effect on a macroscopic scale is ineffective in the momentary state under consideration.

A *state* characterizes the equilibrium of a system on a macroscopic scale, which is based on a dynamic equilibrium on a microscopic scale.
A *state variable* is a macroscopic property of the system in a state.

In the development of machines that exchange heat and/or work with their environment, the clarification of each state is useful in order to achieve similar operations at a later time in the same machine or in other machines.

But, in this context, there appears the problem of reducing the number of state variables (properties) that precisely define a state to a minimum.

The properties of a system on a macroscopic scale are represented by experimentally appointed values of state variables such as *temperature, pressure or volume*. But properties which define a system in a state could also be *the color, the smell or the sound.*

If a state can be fixed by the value pairings of a small number of independent values of state variables (properties), then most of the other properties can also be derived from it.

The state variables that define a state independently of each other are understood as *degrees of freedom of a system.*

In this context, the American scientist Josiah Gibbs (1839-1903) deduced a law that can be considered as a paradigm of phenomenology: **the phase rule.**

For all systems in nature, according to the phase rule, there is a clear relationship between the degrees of freedom (F), the number of chemical components in the system (K) and the respective phases (P) (*gaseous, liquid, solid*):

$$F = K - P + 2$$

Examples: For a homogeneous system with one component (water) and one phase (liquid) the concrete result of this formula is: ***1 – 1 + 2 = 2.***
When heating the liquid water in an open pot (without a fixed lid), both the temperature and the water density in the pot are variable. Meanwhile, the pressure in the water remains constant. So, the two degrees of freedom during heating are the temperature and the density (as reciprocal value of the mass-related volume).

Measuring the temperature and the density value at a precise moment the actual state of the heated water can be exactly characterized.

With a similar kind of water heating using a pressure cooker (with a tight lid, fully filled with water), temperature and pressure change again, while the density remains constant. The two degrees of freedom in this case are the temperature and the pressure. Here, too, their measurement at a certain moment is sufficient to specify the current state.

For a system with one component and two phases, from the formula above can be deduced: ***1 – 2 + 2 = 1.***
In this case, only one state variable is freely selectable, the others then depend on it:

For example, when water is heated beyond the boiling point, there appears a gaseous phase (steam). From this point on, the temperature remains constant despite the continued heat supply. When heated in an open pot, only the water density changes, while the pressure remains, like the temperature, constant. In another case, heating water in a pressure cooker or in a closed reservoir, where the volume, and therefore the water density, remains constant, like the temperature, only the pressure changes.

So far, no gases, gas mixtures or liquids have contradicted Gibbs' phase rule in different phases. The physicist who, due to the atomic behavior (in the microscopic range) in every component and in every phase, is looking for a strictly scientific explanation of the number of degrees of freedom of a system, can really not be envied!

An extreme example of phase rule is given again by the water: This single chemical component can be solid, liquid and gaseous at the same time. In this state, however, all degrees of freedom are "assigned": The temperature must be exactly 0°C, the pressure 0.006 bar, the density in each of the 3 phases is precisely fixed.

Scientists such as the Frenchman Mariotte (1620-1684), the Irishman Boyle (1626-1691), and the Frenchman Gay-Lussac (1778-1850), have found relationships between the three state variables (properties) which are *the pressure, the temperature and the volume* for idealized gases through a variety of experiments and summarized them in formulas: If oxygen (in a further idealization also air, as a gas mixture with known properties) is heated at constant *pressure,* the increase in *volume* is direct proportional to the *temperature* rise. And if the *volume* was constant during heating, the increase in *pressure* is directly proportional to the rise in *temperature*. This resulted in countless formula combinations.

The fire can therefore heat the water in a boiler, which results in both *heat* and *work* in a power plant.

The fire can heat the air in the combustion chamber of an engine. This results in both *heat* and *work*.

In order to be able to build a power plant or an internal combustion engine, one must first deal with the properties of the working medium (water or air) during the state changes:

Lids should not burst due to an enormous pressure, screws should not melt due to a hell temperature, water in the pump of the power plant should not solidify to ice.

7

Work from heat

7.1 Energy exchange

Snapshot in an apartment: The walls to the outside are heat-tight, the entrance door as well, and moreover, it is also closed. No water flows in, no wastewater flows out, the electricity is switched off. Rooms A, B and C are open to each other. In room B, a fire crackles in the large fireplace. Grandpa reads in room C by the light of an oil lamp. The grandchild is constantly making his tricycle rounds through all the rooms, power on the wheels over such a track means a lot of work, but the dwarf has enough energy (Fig. 7.1).

From B to A, but also from B to C, energy flows in the form of heat emitted by the fireplace. The grandson's tricycle carries the energy in the form of work from B to A, occasionally to C, and so on. The flame of grandfather's oil lamp brings light and some heat to room C.

It is the right moment to do the energy balance: Room B gives part of its energy to A and C in the form of heat. The child carries the tricycle work from B to A and then on to C and back to B. The grandpa with his oil lamp could almost be neglected in comparison with so much energy exchange. In each room, the energy level is changed at intervals. But adding up all the energy in the 3 rooms at any time, no change can be detected.

This is nothing else than a form of the phenomenologically deducted "First Law" of thermodynamics. It is a simple insight, which is always and everywhere valid, but every student of technical sciences has so much respect for it! Let us formulate this low in an intelligible form.

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_7

The first law of thermodynamics – general form
Between the subsystems of an energetically isolated system, an energy exchange can take place in such a way that the energy of individual subsystems changes. However, the total energy of the system, as the sum of the energies of the subsystems, remains constant.

The correlations are shown in Fig. 7.1 and described in Eq.(7.1) to Eq.(7.4).

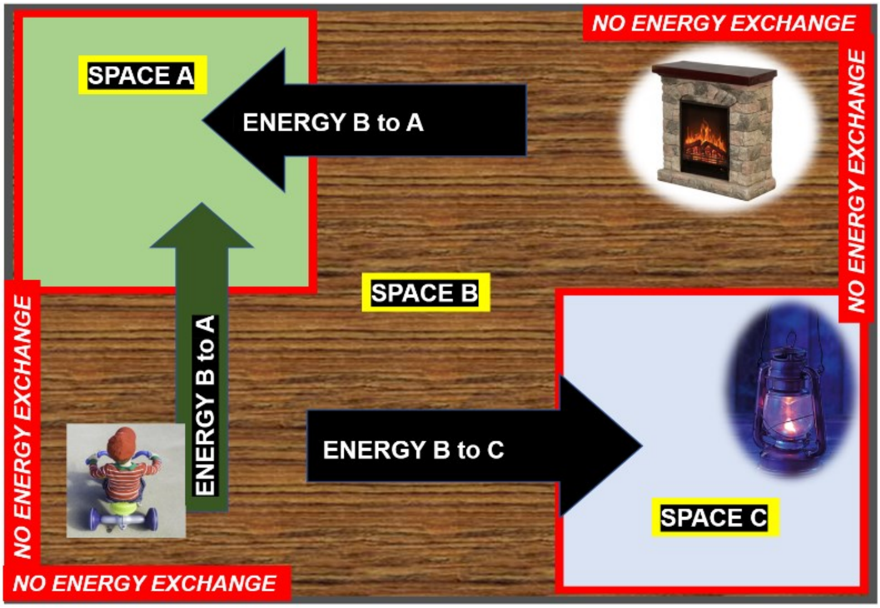

Fig. 7.1 Energy exchange within an energy-tight system related to the environment

$$E_A + E_B + E_C = E_A{}' + E_B{}' + E_C{}' \tag{7.1}$$

with

$$E_A{}' = E_A + E_{B1A} + E_{B2A} \tag{7.2}$$

$$E_B{}' = E_B - E_{B1A} - E_{B2A} \tag{7.3}$$

$$E_C{}' = E_C + E_{B3C} \tag{7.4}$$

However, the entity system-environment is also an energetically tight system (*The limit of the environment at infinity does not allow further energy exchange*). And so, the first law becomes even more interesting (Fig. 7.2):

The First Law – Exchange System-Environment
During the energy exchange between a system and its environment, for example as heat or work, the sum of all forms of energy of the system and the environment remains constant.

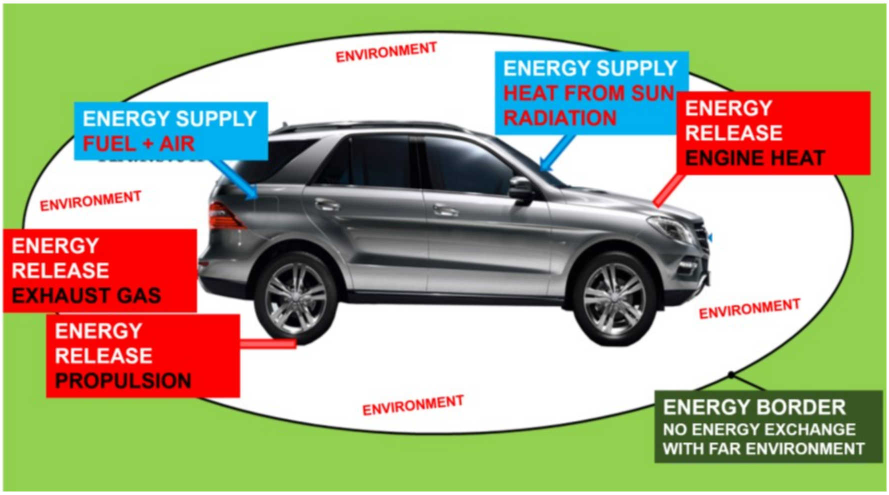

Fig. 7.2 Energy exchange between a system and its environment

One of the many consequences of this law: An engine can only do work as long as it is supplied with the appropriate energy.

An engine that tries to do work without an appropriate energy supply is called a *"perpetual motion machine of the first kind"*.

7.2 Energy balance from one state to another

A process (*a change of state*) between two states of a heated or cooled medium (whether *gas, steam or a liquid)* which performs or receives work in a machine can run following different paths. As an example, either the pressure or the given volume can be kept constant. But it can also be that both pressure and volume are continuing changing during the process.

But that, what comes out at the end (Eq.7.5), is independent of the path of changing state, as demonstrated in Chapter 2 of [1]!

$$Q_{1a2} - W_{1a2} = Q_{1b2} + W_{1b2} = const. \tag{7.5}$$

Q_{1a2}	$[J]$	heat from state 1 to 2 following path a
Q_{1b2}	$[J]$	heat from state 1 to 2 following path b
W_{1a2}	$[J]$	work from state 1 to 2 following path a
W_{1b2}	$[J]$	work from state 1 to 2 following path b

Although the work and the heat are process quantities (path-dependent), their sum or difference, depending on whether supplied or discharged, is a thermodynamic property (path-independent). Such property characterizes the initial state, then the final state of the medium [1].

For a medium which is embedded within the system, this thermodynamic property (state variable) is the internal energy.

Examples of closed systems with embedded medium:

- *a pressure cooker, fully filled with water*
- *a metal can with lid, fully filled with coffee*
- *a balloon, fully filled with a gas*
- *the burned gas within a piston engine during expansion.*

The internal energy comprises several forms of energy that can only be detected on a microscopic scale, the main form of them being the kinetic energy of the particles.

The First Law – State Changes in Closed Systems
The exchange of heat and work between a closed system and its environment during a change of state corresponds to the variation of its internal energy.

The First Low can be mathematically formulated as shown by Eq. (7.6) and Eq. (7.7).

$$Q_{12} - W_{12} = U_2 - U_1 \tag{7.6}$$

(when $Q_{12} = W_{12}$, then $U_2 = U_1$, $\Delta U = 0$)

$$q_{12} - w_{12} = u_2 - u_1 \tag{7.7}$$

Q_{12}	$[J]$	heat exchanged from state 1 to 2
W_{12}	$[J]$	work exchanged from state 1 to 2
U	$[J]$	internal energy in a state (1 or 2)
q_{12}	$\left[\frac{J}{kg}\right]$	specific heat from state 1 to 2
w_{12}	$\left[\frac{J}{kg}\right]$	specific work from state 1 to 2
u	$\left[\frac{J}{kg}\right]$	specific internal energy in a state (1 or 2)

An open system exchanges working medium with the environment, as opposed to a closed system.

Examples of open systems with a flowing working medium (working fluid):

- *a gas turbine as aircraft propulsion*
- *a steam turbine in the power plant*
- *water pumps, radiators, nozzles.*

In open systems in which a flow of the working medium occurs, in addition to the internal energy, as in closed systems, there appear supplementary flow-specific forms of energy: these are the pumping work, the kinetic energy, and the potential energy, as shown in Eq. (7.8), Eq. (7.9) and Eq. (7.10). The sum of these forms of energy (internal energy, pumping work kinetic energy and potential energy) in a state is called, as already mentioned, enthalpy.

The First Law – State Changes in Open Systems
The exchange of heat and work between an open system and its environment during a change of state corresponds to the variation of its enthalpy.

$$Q_{12} - W_{12} = {H_2}^* - {H_1}^* \tag{7.8}$$

$$\left(\text{with } H^* = U + pV + \frac{mc^2}{2}\right) \tag{3.3}$$

$$Q_{12} - W_{12} = H_2 - H_1 \ \left(\text{if } H^* \cong H \text{ , when } U + pV \gg \frac{mc^2}{2}\right) \tag{7.9}$$

$$q_{12} - w_{12} = h_2 - h_1 \tag{7.10}$$

H^*		$[J\,;\mathrm{Nm}]$	total enthalpy in a state (1 or 2)
p		$\left[\frac{\mathrm{N}}{\mathrm{m}^2}\right]$	pressure
V		$[\mathrm{m}^3]$	volume
pV		$[J\,;\mathrm{Nm}]$	pumping work
m		$[kg]$	fluid mass
c		$\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	fluid speed
$\frac{mc^2}{2}$		$[J\,;\mathrm{Nm}]$	kinetic energy
h		$\left[\frac{J}{kg}\right]$	specific enthalpy in a state (1 or 2)

During many processes in machines and plants, there is no heat exchange or no work exchange. This simplifies the balance of the energy exchanged.

The following examples present the most frequent categories:

- closed systems without heat exchange but with work exchange or without work exchange but with heat exchange

and

- open systems without heat exchange but with work exchange or without work exchange but with heat exchange.

Closed systems: work without heat exchange

Examples:
- *heat-insulated air pump*
- *piston compressor without cooling*
- *piston engine without cooling during expansion*

In such a case, described by Eq. (7.11) and Eq. (7.12) the work that must be done for compression or that can be obtained from the expansion corresponds to the variation of the internal energy of the trapped gas (air or burned gas). It can be easily deducted if the process was a compression or an expansion: if the internal energy of the gas increased after the process, it was a compression, if it decreased, it was an expansion.

$$\cancel{Q_{12}} - W_{12} = U_2 - U_1 \tag{7.11}$$

$$\text{thus} \quad W_{12} = U_1 - U_2 \tag{7.12}$$

$$(\underset{\text{expansion}}{U_2 > U_1 \rightarrow W_{12} > 0} \, ; \; \underset{\text{compression}}{U_2 < U_1 \rightarrow W_{12} < 0})$$

Closed systems: heat exchange without work

Examples:
- *combustion in the closed combustion chamber of a piston engine (Fig. 7.3)*
- *heating of the air in a car tire due to friction of the rubber on the road surface while driving*
- *heating the water in Grandma's bath boiler*
- *cooling of the white wine in a bottle.*

$$Q_{12} - \cancel{W_{12}} = U_2 - U_1 \tag{7.13}$$

$$\text{thus} \quad Q_{12} = U_2 - U_1 \tag{7.14}$$

$$(\underset{\text{cooling}}{U_1 > U_2 \rightarrow Q_{12} < 0} \, ; \; \underset{\text{heating}}{U_1 < U_2 \rightarrow Q_{12} > 0})$$

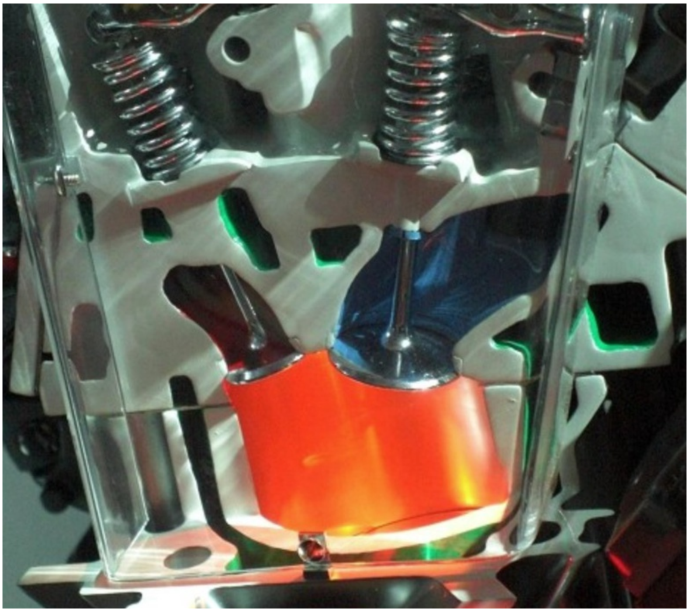

Fig. 7.3 Combustion in the closed combustion chamber of a piston engine

In the first three cases, the heat supplied corresponds to the increase in the internal energy of the gas mixture in the piston engine, of the air in the tire, and of the water in the bath boiler. In the fourth case, the heat extraction from the white wine in the bottle corresponds to the reduction of its internal energy.

Open systems: work without heat exchange

Examples:
- *thermally insulated centrifugal and axial compressor (Fig. 7.4)*
- *uncooled radial and axial turbines (Fig. 7.4)*
- *Water, fuel and oil pumps*

$$\cancel{Q_{12}} - W_{12} = H_2{}^* - H_1{}^* \tag{7.15}$$

thus $$W_{12} = H_1{}^* - H_2{}^* \tag{7.16}$$

$$(H_1{}^* > H_2{}^* \rightarrow \underset{\text{expansion}}{W_{12} > 0} \; ; \; H_1{}^* < H_2{}^* \rightarrow \underset{\text{compression}}{W_{12} < 0})$$

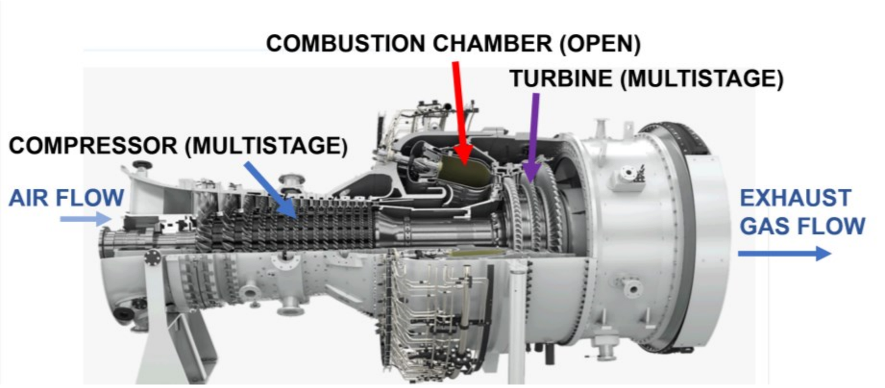

Fig. 7.4 Functional modules in turbomachinery (gas turbines): axial compressor and turbine, centrifugal compressor and turbine, open combustion chambers

In such a case, the work that must be done for compression or that can be obtained from the expansion corresponds to the enthalpy variation of the flowing gas (air or burned gas). It can be easily deducted if the process was a compression or an expansion: if the enthalpy in the gas increased after the process, it was a compression, if it decreased, it was an expansion.

Open systems: heat exchange without work

Examples:
- *heat exchangers: coolers and radiators*
- *combustion chamber of a turbomachinery (gas turbine) (Fig. 7.4)*

In the case of the combustion chamber in the gas turbine, the heat supplied corresponds to the increase in the enthalpy of the flowing gas between chamber entry and exit.

$$Q_{12} - \cancel{W_{12}} = {H_2}^* - {H_1}^* \qquad (7.17)$$

$$\text{thus} \quad Q_{12} = {H_2}^* - {H_1}^* \qquad (7.18)$$

$$(\, {H_2}^* > {H_1}^* \;\rightarrow\; \underset{\text{heat supply}}{Q_{12} > 0} \;;\; {H_2}^* < {H_1}^* \;\rightarrow\; \underset{\text{heat release}}{Q_{12} < 0} \,)$$

The variation of enthalpy between input and output of the water flow in a cooler or in a radiator is, similarly, an indicator of the amount of exchanged heat.

Flows without heat and work exchange

Examples:

- *Flows through heat-insulated pipes and nozzles (Fig. 7.5)*

Fig. 7.5 Exhaust gas flow through the nozzles of the jet engines of an aircraft (Source: Eurofighter Typhoon F2, RAF)

Neither heat nor work between the input and the output from a pipe or from a nozzle, this means that the enthalpy of the respective flow does not change at all.

$$\cancel{Q_{12}} - \cancel{W_{12}} = {H_2}^* - {H_1}^* \qquad (7.19)$$

$$\text{thus} \quad {H_2}^* = {H_1}^* = const. \qquad (7.20)$$

Is such a case of interest at all? You bet! The enthalpy consists principally of internal energy, pumping work and kinetic energy.

The relationships between these 3 forms can be changed through targeted measures. The best example of this is the nozzle in a gas turbine:

The nozzle inlet has a larger diameter or flow cross-section than the nozzle output. The exhaust gas is thereby accelerated. That is, the pumping work is increasingly converted into kinetic energy, the flow velocity increases while the pressure decreases. Between input and output from the nozzle, however, the enthalpy (the total energy) of the gas has not changed at all!

The effect of this gas acceleration is enormous: between the inlet of the air into the intake pipe of the machine and the output of the exhaust gases through the nozzles, the flow velocity (meters per second) has changed considerably. In connection with the transferred mass flow of the burned gas (kilograms per second), this results in a force (Newton) that is exerted by the flow on the ambient air. But the air in the atmosphere is much, much larger, and reacts to it by not changing its state at all, but pushing the culprit forward, with the same force. That's the responsiveness! In this case it is obtained only by accelerating exhaust gas in nozzles in which nothing else occurs, neither work nor heat exchange. Therefore, all modules in the machine (compressor, combustion chamber, turbine) serve only this one purpose: the acceleration of exhaust gases in the nozzle. The actual work only appears outside the machine. It corresponds to the developed force multiplied by the flight distance (Newton meters, or joules).

Basically, regardless of acceleration nozzles, this is similar when rowing on the lake: In this case, you accelerate the water between the bow and stern of the boat when paddling. The water is in this case also much, much larger and pushes, analogously, the culprit forward, with the appropriate reactive power.

Finally, two recommendations related to reaction forces could be of interest:

- man should not stay behind a turbojet accelerating on the ground. What or who is not as big as the ambient air is swept away with vehemence.
- you should not row in the bathtub, the water in such a small pool does not exert any reactive power, but it spills out.

8

Working fluids as carriers of heat and work

8.1 Air and water are working fluids, fuel is not

What is the actual task of a working fluid? The answer is clear: many! At first, it should be able to flow continuously.

Furthermore, it should be able to absorb or to release via heat exchanger so much heat as possible in a very short time. It must neither freeze at low temperatures nor decompose at high temperatures.

A phase change from gas to liquid and vice versa must be precisely controllable in order not to damage liquid pumps or steam turbines in the circuits of power plants, for example.

A working medium, which also includes the refrigerants, should not be toxic or easily flammable, nor must it cause an ozone hole in the earth atmosphere.

Above all, however, it must be inexpensive, available everywhere and easy to store.

Air

For the direct effect of a fire in internal combustion engines, in gas turbines and in any other type of heat engine (Chapter 3.2) air *(21% oxygen and 78% nitrogen, 1% several other gases)* is by far the most widespread working fluid. Air can be compressed up to 1000 bar or heated up to 1000°C without changing its chemical structure or becoming liquid. On the other hand, air can be cooled down to *minus*

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_8

195 °C before it becomes liquid. The oxygen from the air reacts directly with all types of fuel, from gasoline and methanol to rapeseed oil and hydrogen.

The thermodynamicists, and in particular the engineers who develop combustion engines, consider in an initial phase of calculations the fuels "only" as heat generators for the air, which can be “heated” in this manner to temperatures above 2500°C, “ignoring” the chemical reactions provoked by combustion. In a further approximation, the air after the heat supply is considered as a gas mixture of carbon dioxide, water superheated steam and nitrogen, whose parameters can be determined exactly, like those of any other gas [1] .

Water

Water is used for the indirect action of fire to create pressure for work (Chapter 3.2) in power stations with boilers and gas turbines, in heating systems of all kinds or in steam locomotives. The water is heated above 100°C at 1 bar or over 300°C at 100 bar [1] to superheated steam, i.e. completely "dry", without any traces of liquid. This is exactly what the steam turbine gets the most, similar to the superheated gas mixture in the gas turbine of a jet fighter.

In cooling circuits of piston engines or gas turbines that have to do with fire, even if indirectly, water is also used as a working fluid. Due to the risk of frost, the water in such cooling circuits also contains some additives.

Working fluids for machines without fire

In refrigerators, no water can be used as a working fluid, because it would form ice plugs in the circuit, at temperatures below 0 ° C. Similar derivatives of petroleum such as propane or butane, ammonia, dichlorodifluoromethane (freon) and chlorofluorocarbons (CFCs) are suitable for this purpose.

In air conditioning systems have been introduced recently, as a working fluid, carbon dioxide. Previously tetrafluoroethene (R134a) was the most commonly used medium.

Air as ideal gas

Among all these working fluids, the air is not only one of the most efficient but also the simplest in its structure. For the calculation or analysis of the processes in heat engines working up to very high temperatures or in refrigeration systems which act at extremely low temperatures, the working medium air is considered from a thermodynamic point of view as an "ideal gas" *(even if it is actually a mixture of oxygen and nitrogen):*

The gases, such like air, differ from liquids and solids by a simpler thermal behavior. A gas takes up all the available volume, which indicates very low interaction forces between its particles. These interaction forces become smaller the lower the pressure or the higher the temperature of the gas. As a result, the distances between the particles of a gas become so large that their own volume becomes negligible.

By extrapolating these conditions, the model of an ideal gas is formed. The advantage of the model lies in a simpler, clearer analysis of the thermodynamic processes when using gases. It allows to establish a direct relationship between the essential state variables which are the pressure, the volume and the temperature [1].

These three state variables are interdependent, the proportions to each other being given by the gas mass and by their ideal, specific gas constant, as shown in Eq. (8.1). The ideal gas constant for a specific gas can be easily obtained, when dividing the universal gas constant at their fixed value by the molar mass of the respective gas. The Eq. (8.1) can be also expressed in the form (8.2) using the gas density as mass-to-volume ratio.
The model of the ideal gas and the resulting relationships are applicable in a wide range of pressure and temperature values for each real gas with sufficient accuracy. Deviations become more or less evident with increasing pressure or decreasing temperature, depending on the type of gas.

A pragmatic way for the allowance of such deviations from the relationships which are applied for ideal gases is the introduction of a real gas factor, as shown in Eq. (8.1 R) and Eq. (8.2 R).

for ideal gases

$$pV = mRT \tag{8.1}$$

or $p = \frac{m}{V} \cdot RT$ with $\frac{m}{V} = \rho$

$$p = \rho RT \tag{8.2}$$

for real gases

$$pV = Z \cdot mRT \tag{8.1 R}$$

$$p = Z \cdot \rho RT \quad \text{with} \quad R = \frac{\bar{R}}{\bar{M}} \tag{8.2 R}$$

p	$\left[\frac{N}{m^2}\right]$	pressure
V	$[m^3]$	volume
m	$[kg]$	fluid mass
R	$\left[\frac{J}{kg\ K}\right]$	ideal gas constant (for a specific gas)
T	$[K]$	temperature
ρ	$\left[\frac{kg}{m^3}\right]$	density
$\bar{R}$	$\left[\frac{J}{kmol\ K}\right]$	universal gas constant ($\bar{R} = 8314 \pm 04\ \frac{J}{kmol\ K}$)
$\bar{M}$	$[kmol]$	molar mass of a specific gas
Z	$[-]$	real gas factor

However, the simplest way to analyze the behavior of a real gas in a state or during a change of state is to simultaneously measure pressure, volume, (or density), and temperature. For frequently used gases, such values are available in physical tables.

Heat capacity of the air as a working medium

How much heat can absorb or release the air, as a working medium in a heat exchanger? This is determined by its heat capacity. Such a property, like many others in the case of the air or any other working medium, is always given for 1 kilogram, i.e. mass-related. Mass-related quantities are often referred to as "specific quantities".

The specific heat capacity of a substance, which can be also air, is defined as the energy (heat) required to increase the temperature of its unit of mass (1 kg) by 1 Kelvin.

1 Kelvin gives (- 273.15 + 1) ° C. However, when it comes to increasing the temperature from degree to degree, which represents a difference, this can also be measured and expressed in °C.

The specific heat capacity, like the heat itself, is a process variable (path-dependent). It has therefore not the same value when the heat has been supplied or released at a constant volume or at a constant pressure.

The specific heat capacity depends on the type of fluid, in this case the air, and is usually determined experimentally in physics laboratories and recorded in tables accessible to everyone.

Its utilization is particularly important for the determination of the energy exchange in a process, whether in a power plant or in a piston engine:

- The heat capacity measured at a constant volume, multiplied by the temperature in a given state of the working fluid, yields the energy in that state.
- The heat capacity measured at constant pressure, multiplied by the temperature in a given state of the working fluid, yields the enthalpy in that state.

The specific heat capacity for air at constant volume or pressure can be determined in a very precise manner:

- *the air is firstly trapped in a vessel with a tightly screwed lid (for measurement at constant volume) or in a vessel with a movable lid sliding close to the walls of the vessel (for measurement at constant pressure).*
- *the air is then heated by means of an electric heating spiral that surrounds the vessel.*
- *finally, when measuring the heating power (P) and the respective temperature rise (T) at the same intervals (t), the heat supply (Q) for the amount of material (m) – and thus the specific heat capacity – can be derived.*

The following characteristics of the heat capacity are significant [1]:

$$c = \frac{Q_{12}}{m\,\Delta T} \tag{8.3}$$

$$c_P - c_V = R \tag{8.4}$$

c	$\left[\frac{J}{kg\ K}\right]$	specific heat capacity of a substance
Q_{12}	$[J]$	heat exchanged from state 1 to 2
ΔT	$[K]$	difference of temperatures
c_P	$\left[\frac{J}{kg\ K}\right]$	specific heat capacity at constant pressure
c_V	$\left[\frac{J}{kg\ K}\right]$	specific heat capacity at constant volume

- the specific heat capacity depends on the temperature: for example, between 30°C and 31°C it is lower than between 70°C and 71°C.
- the values of the specific heat capacity of a gas at constant pressure are always greater than those at constant volume. A heat capacity at constant pressure can be calculated by adding a constant value (*the gas constant of the respective substance*) to the specific heat capacity at a constant volume for a gas, at any temperature.

- the specific heat capacity at constant volume or pressure depends on the respective substance *(e.g. air, water, carbon dioxide, methane)* (Fig. 8.1).

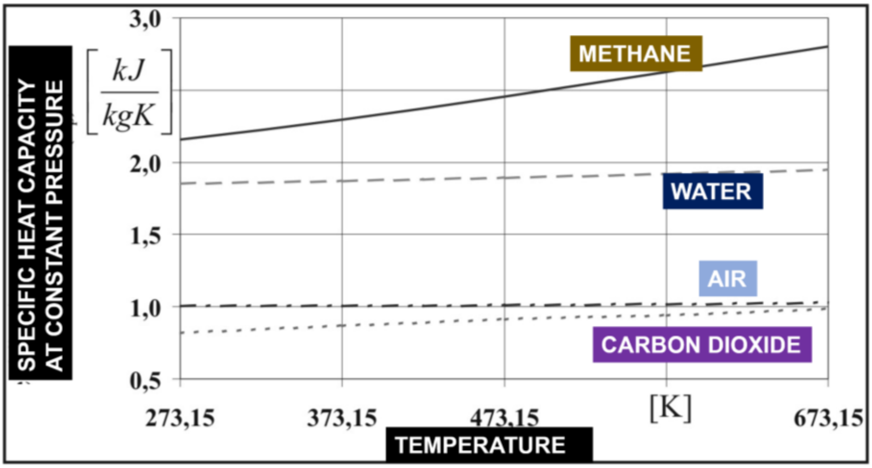

Fig. 8.1 Specific heat capacities at constant pressure and at constant volume of different gases for various temperatures.

Gas mixture

When carrying out processes with combustion, the working medium is often transformed into a different gas mixture.

Example: the exhaust gas components after combustion in an internal combustion engine or in a gas turbine: carbon dioxide, water vapor, nitrogen, partly also carbon monoxide, unburned hydrocarbons, nitrogen oxides, oxygen)

To describe the states and the state changes in ideal gas mixtures, it is assumed that the individual gas components do not react chemically with each other during a state change without combustion.

The correlations between their mass and volume fractions, the density of a mixture and the heat capacity at constant pressure and at constant volume *(from which the internal energy and enthalpy can be derived*) can be easily calculated on the basis of simple formulas from spreadsheets.

8.2 Elementary changes of state with gases as working fluids

The changes of state as different process sequences within a gas or gas mixture, in which a state variable *(pressure, volume, temperature)* or a certain combination of these remain constant, are often considered as elementary changes of state.

In general, for many applications, following data are to be determined:

- the energy exchange during heat supply (Q_{in}), heat release (Q_{ex}), work supply (W_{in}), work release (W_{ex}),
- the extreme values of the state variables such as pressure (p), volume (V) and temperature (T) between the beginning and the end of the said change of state.

The following examples are representative for such elementary changes of state.

Changes of state at constant volume

An energy exchange between a technical system or module and its environment at a constant volume of the working medium generally leads to a change of the other state variables.

Examples

(Fig. 8.2):

Closed systems:	*heat supply by combustion in a gasoline engine (as an ideal change of state)*
	heating a medium in a closed vessel
Open systems:	*pumping an incompressible medium (gasoline, water)*

In a closed system, such as the gasoline engine Fig. 8.2 a), the combustion speed is much higher than the piston speed:

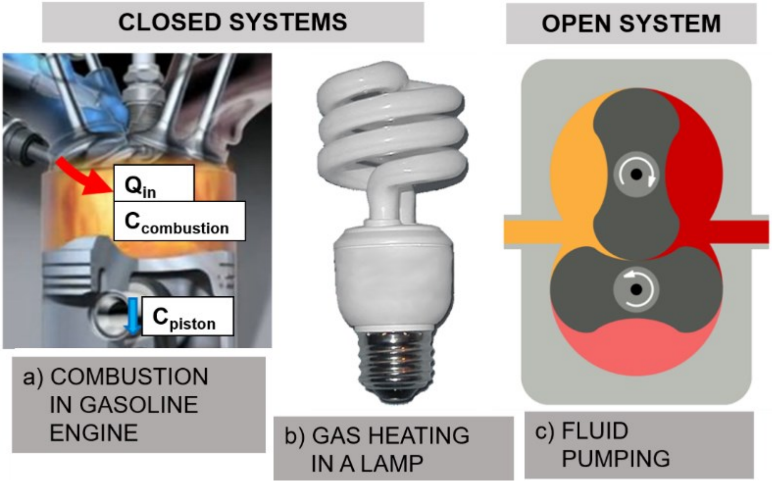

Fig. 8.2 Examples of state changes at constant volume of the working medium as gas (a, b) and as liquid (c).

$$\frac{p_1}{T_1} = \frac{p_2}{T_2} = \frac{mR}{V} \tag{8.5}$$

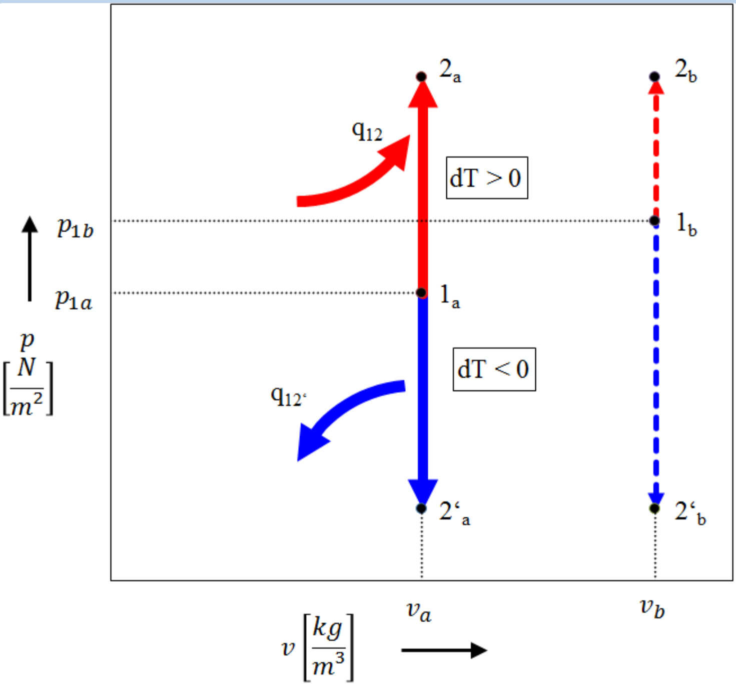

Fig. 8.3 Examples of state changes at constant volume of the working medium as gas

You can therefore assume that the piston does not move at all during combustion. This means, the state change takes place at constant volume. The increase in pressure in this case is directly proportional to the temperature increase as a result of combustion.

Such state changes are represented in Fig. 8.3 for two different values of the (constant) volume of the working medium as gas, in the case of a heat supply (red) and of a heat release (blue).

The heat supply corresponds to the variation of the internal energy of the working fluid, as shown in Eq. (8.6) and Eq. (8.7). Considering that the internal energy is a function of the specific heat capacity at constant volume, the calculation of the heat supply can be expressed as shown in Eq. (8.8) and easily calculated using the form in Eq. (8.9).

$$Q_{12} = U_2 - U_1 \tag{8.6}$$

$$q_{12} = u_2 - u_1 \tag{8.7}$$

$$q_{12} = \int_{T_1}^{T_2} c_V (T_2 - T_1) \tag{8.8}$$

$$q_{12} = c_{Vm}(T_2 - T_1) \tag{8.9}$$

Q_{12}	$[J]$	heat exchanged from state 1 to 2
U	$[J]$	internal energy in a state (1 or 2)
q_{12}	$\left[\frac{J}{kg}\right]$	specific heat from state 1 to 2
u	$\left[\frac{J}{kg}\right]$	specific internal energy in a state (1 or 2)
c_{Vm}	$\left[\frac{J}{kg\ K}\right]$	middle specific heat capacity at constant volume
T	$[K]$	Temperature in a state (1 or 2)

Changes of state at constant pressure

An energy exchange between a technical system or module and its environment at constant pressure can occur in both closed and open systems.

Examples	
(Fig. 8.4):	
Closed systems:	*heat supply by combustion in a diesel engine (as an ideal change of state)*
Open systems:	*heat supply by combustion in the combustion chamber of a gas turbine (as an ideal change of state)*

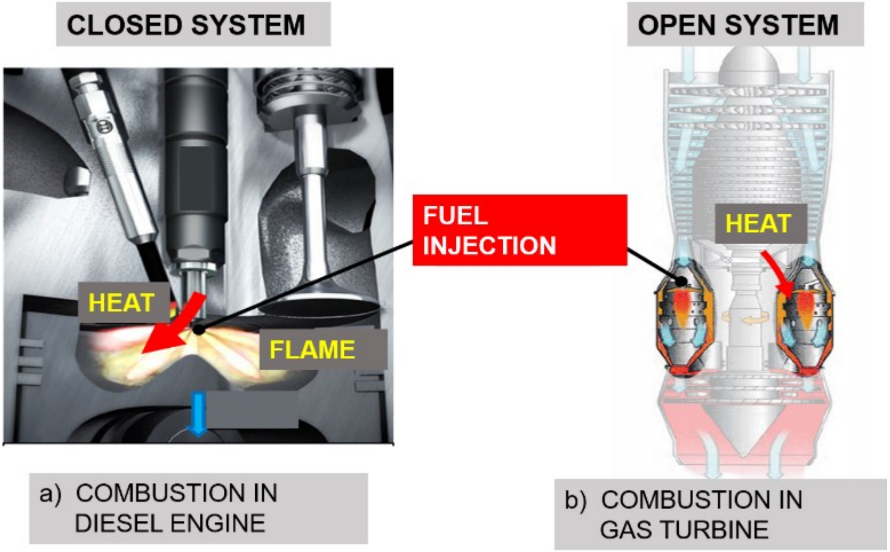

Fig. 8.4 Examples of state changes at constant pressure of the working medium as a gas

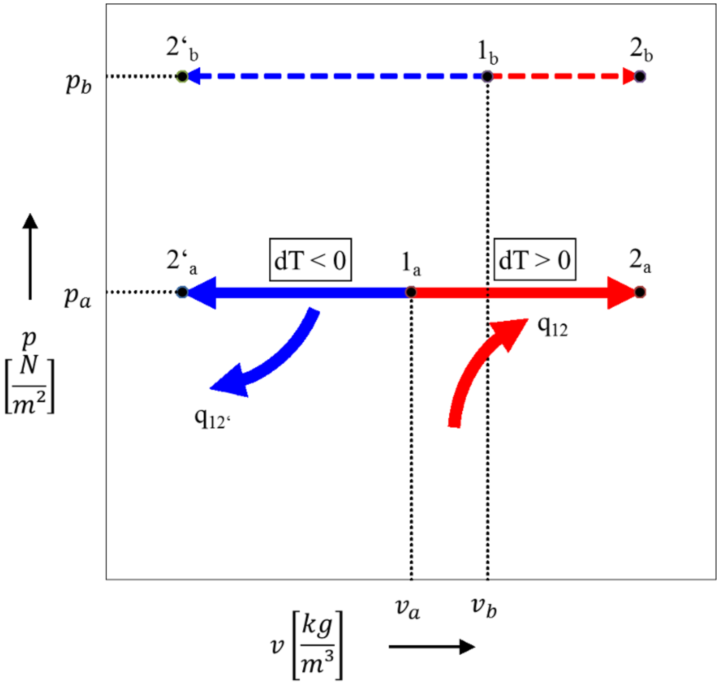

Fig. 8.5 Examples of state changes at constant pressure of the working medium as gas

During such a change of state in a closed system, as in the diesel engine in (Fig. 8.4 a), the combustion speed is slower than that in a gasoline engine, due to the characteristic ignition by compression. As a result, this speed is almost equal to the piston speed. The pressure would increase with the temperature, because of the combustion, but the concomitant increase in volume acts as a compensation. This means that the change of state takes place largely at constant pressure. The temperature increase in this case is directly proportional to the change in volume.

Such state changes are represented in Fig. 8.5 for two different values of the (constant) pressure of the working medium as gas, in the case of a heat supply (red) and of a heat release (blue).

The heat exchange during a change of state results from the multiplication of the heat capacity of the gas at constant pressure by the temperature difference resulting from combustion.

This relationship is shown in Eq. (8.10) in integral form and in Eq. (8.11) when using a middle specific capacity at constant pressure.

During such a process in a closed system, however, work appears as well: it results from the multiplication of the constant pressure by the volume change. This is a typical behavior for Diesel engines when heat is supplied [1].

$$q_{12} = \int_{T_1}^{T_2} c_p(T)dT \tag{8.10}$$

$$q_{12} = c_{pm}(T_2 - T_1) \tag{8.11}$$

c_{pm}	$\left[\frac{J}{kg\ K}\right]$	middle specific heat capacity at constant pressure

During a similar change of state in open systems, such as in a jet engine (Fig. 8.4 b), both the air flow through the combustion chamber, as well as the fuel flow through the nozzle, are continuous. As a result, the combustion takes place like in the mentioned closed combustion chamber of a diesel engine, thus at constant pressure.

The heat supply during this change of state results (as in the diesel engine) from the multiplication of the heat capacity of the gas at constant pressure by the temperature difference as a result of combustion.

No work appears in such a combustion chamber with flowing medium. Work would be generated in this kind of open system only by a pressure change[1].

Changes of state at constant temperature

An energy exchange as heat and work is possible in a system or module at a constant temperature as well, although the term "temperature" is always associated with heat: *“no temperature change, no heat exchange during a change in the state of a working medium”*. That is far from the reality!

During compression in a piston engine, just like in an air pump, the air would more or less heat up. By a concomitant, correspondingly strong cooling, the scheduled pressure can be achieved, even if the temperature does not rise!

Examples

(Fig. 8.6):

Closed systems: *heat release due to strong cooling during compression of the working fluid in a piston engine*

Open systems: *heat supply by heating during the expansion of the gas flow in a nozzle*

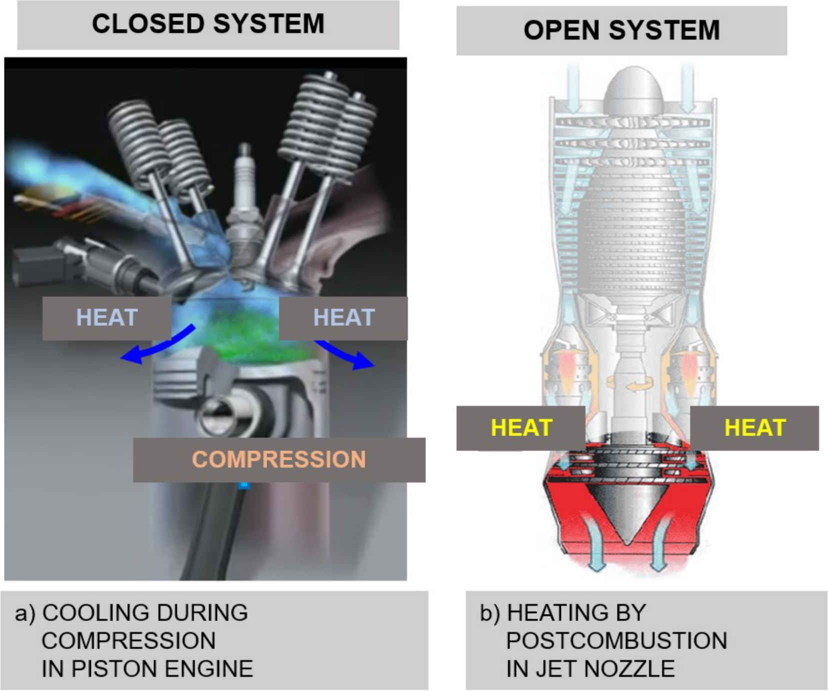

Fig. 8.6 Examples of state changes at constant temperature of the working medium as a gas

The heat supply or the heat release during such a change of state corresponds exactly to the released or supplied work, as shown by the Eq. (8.12) and Eq. (8.13). On his part, the work can be calculated by means of relatively simple formulas, taking into account the pressure and volume variations[1].

Such state changes are represented in Fig. 8.7 for two different values of the (constant) temperature of the working medium as gas, in the case of a heat supply (red) and of a heat release (blue).

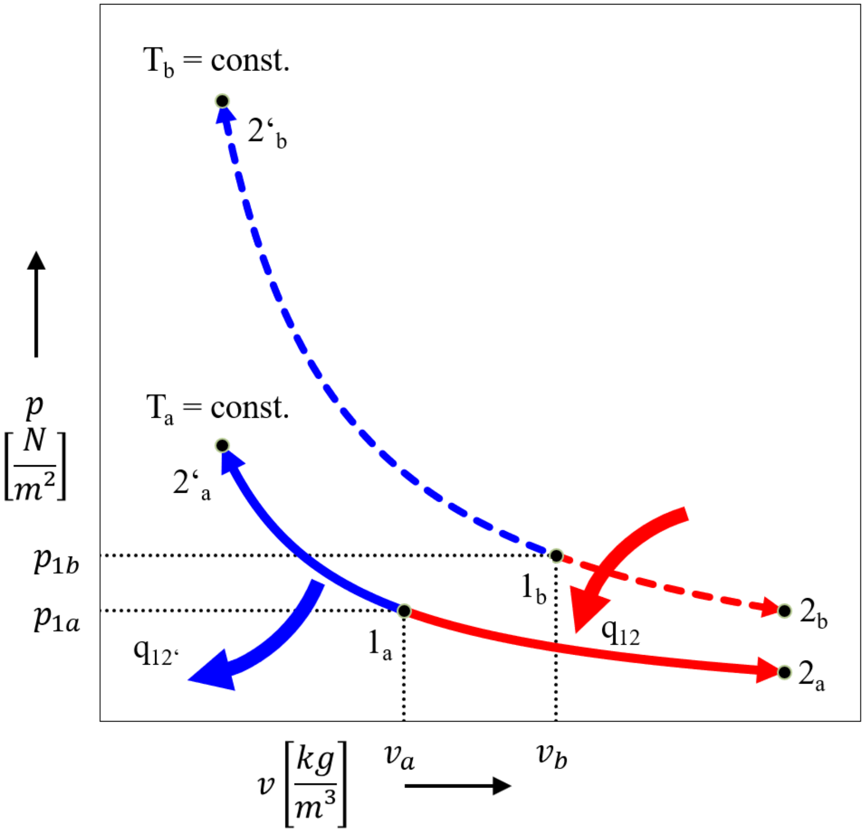

Fig. 8.7 Examples of state changes at constant temperature of the working medium as gas

The relationship between the work - which corresponds to the exchanged heat - and the volume ratio or the pressure ratio is shown in Eq. (8.14), being deducted in base of the definition of the work in closed or in open systems.

$$Q_{12} = W_{12} \tag{8.12}$$

$$q_{12} = w_{12} \tag{8.13}$$

$$q_{12} = RTln\left(\frac{v_2}{v_1}\right) \ , \ q_{12} = RTln\left(\frac{p_1}{p_2}\right) \tag{8.14}$$

Q_{12}	$[J]$	heat exchanged from state 1 to 2
W_{12}	$[J]$	work exchanged from state 1 to 2
q_{12}	$\left[\frac{J}{kg}\right]$	specific heat from state 1 to 2
w_{12}	$\left[\frac{J}{kg}\right]$	specific work from state 1 to 2
v	$\left[\frac{\mathrm{m}^3}{kg}\right]$	specific volume in a state (1 or 2)

Changes of state without heat exchange

Energy exchange in heat-tight systems is however possible, in form of work.

Examples

(Fig. 8.8):

Closed systems:	*compression or expansion in a heat-tight piston engine*
Open systems:	*compression in an axial or radial, heat-insulated compressor; expansion in a radial or axial heat-tight turbine*

Such state changes are represented in Fig. 8.9 for two different values of the (constant) isentropic combination of pressure and volume (pv^k) of the working medium as gas, in the case of temperature increase and of temperature decrease.

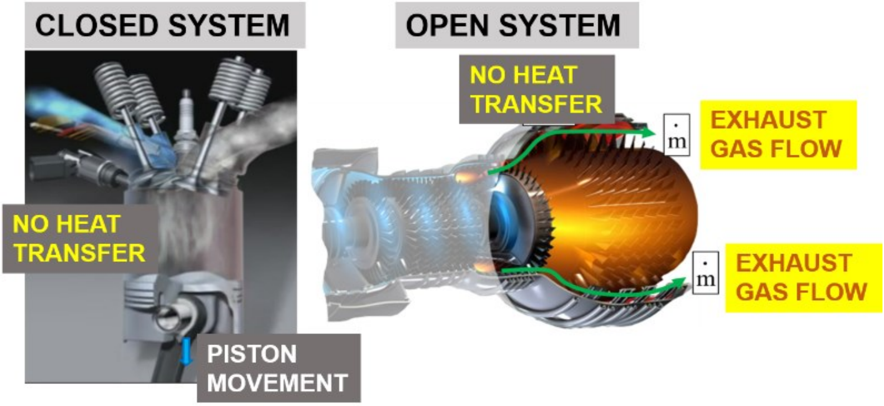

Fig. 8.8 Examples of state changes without heat exchange of the working medium as a gas

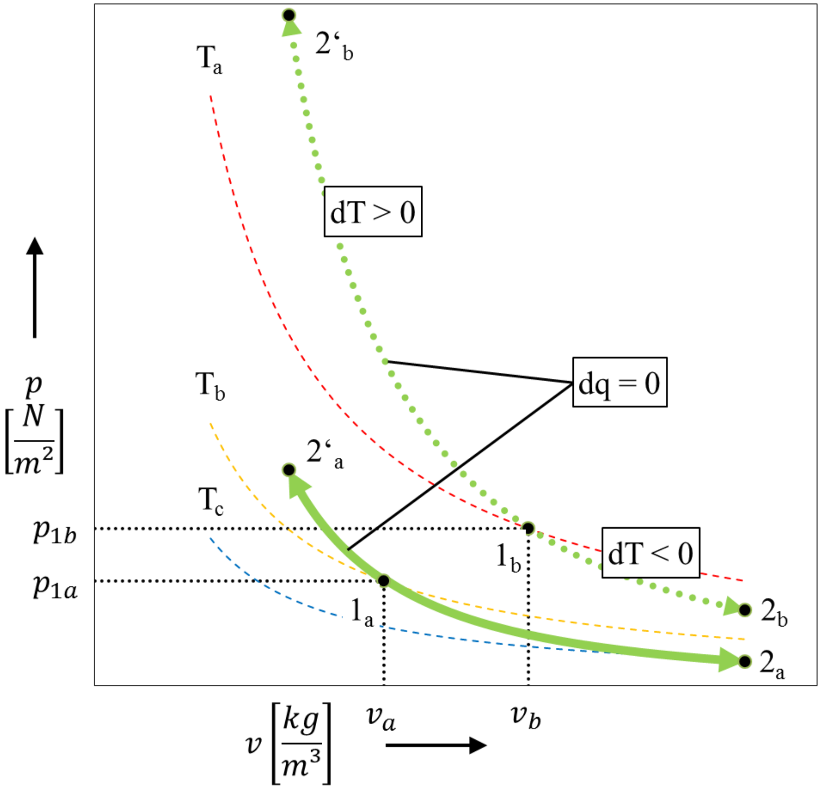

Fig. 8.9 Examples of state changes without heat exchange of the working medium as a gas

In such processes, there appears neither heat supply nor heat release.

On the other hand, in thermally insulated, closed or open systems, work can be generated as a result of compression or expansion. This work can be calculated using relatively simple formulas, taking into account the temperature, pressure and volume variations, as shown in Eq. (8.15) [1].

$$w_{v12} = mc_v(T_2 - T_1) \tag{8.15}$$

The specific work can be expressed also in following form:

$$\begin{aligned} w_{v12} &= c_v T_1\left(1 - \frac{T_2}{T_1}\right) = c_v T_1\left[1 - \left(\frac{V_1}{V_2}\right)^{\kappa-1}\right] \\ &= c_v T_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}\right] \end{aligned} \tag{8.15a}$$

$$W_{p12} = \kappa W_{v12} \tag{8.16}$$

$$\text{with } \kappa = \frac{c_p}{c_v} \tag{8.17}$$

κ	$[-]$	isentropic exponent

Polytropic changes of state

The term "polytropos" comes from ancient Greek, meaning “adaptable". A polytropic change of state represents a generalization of all the elementary changes of state which were described above.

Examples

(Fig. 8.10):

Closed systems:	*compression or expansion in an arbitrarily cooled piston engine*
Open systems:	*compression in an axial or radial compressor with arbitrarily cooling; expansion in a radial or axial turbine with arbitrarily cooling*

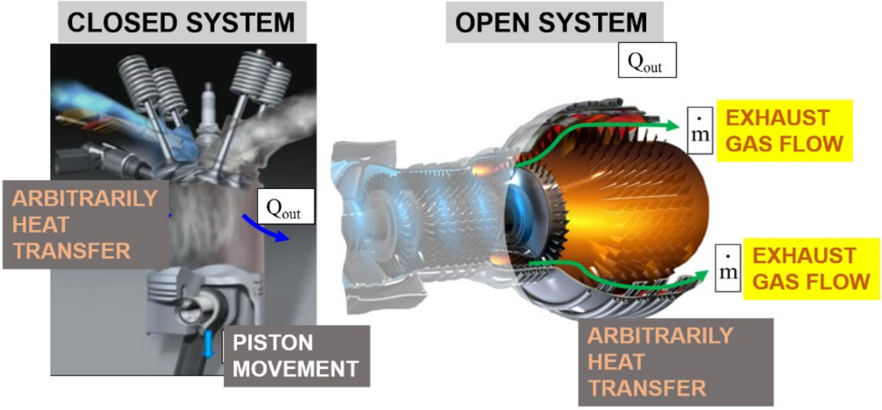

Fig. 8.10 Examples of polytropic state changes of the working medium as a gas

During a polytropic change of state, both heat and work can be exchanged. Such a change of state also requires a new definition of heat capacity, as an extension of those at constant pressure and at constant volume.

The exchanged heat and the exchanged work are calculated with formulas depending on this heat capacity as well as the pressure, volume and temperature change [1].

Elementary changes of state linked in thermodynamic cycles

A promising propulsion system for automobiles, an energy-efficient power plant and a climate-neutral heat pump have a common basis: the fire.

Their creation never begins with the construction of a mechanically and technically revolutionizing plant in the hope that the respective working fluid will then generate miracles.

The creation begins, conversely, with the working fluid itself!

If the machine should constantly deliver work or heat, the changes of state within the process sequences which are carried out by the working fluid must be continuously generated. This is only possible if the overall process can start again and again from the same point. To do this, the changes of state must be combined as a closed chain: and in this manner a **thermodynamic cycle** is created!

It would be inconceivable, after compression and combustion, to constantly relieve the piston of a diesel engine in order to constantly create *work. Its expansion hub would then stretch from Berlin to Munich, where the car itself wants to go!*

It is more advisable to interrupt *the expansion stroke by means of* a *crank mechanism and to send the piston back to compression stroke* as often as work *is required. This is how a cyclic process have to be implemented!*

The elementary changes of state, at constant pressure, volume or temperature, or without heat exchange, are true living cells: their smart combinations can create new, often revolutionary functions. The calculation of the minimum and of the maximum values for *pressure, volume and temperature* in the corner points of such a thermodynamic cycle helps in the choice of materials, in the strength-appropriate design and in the weighing of dimensions.

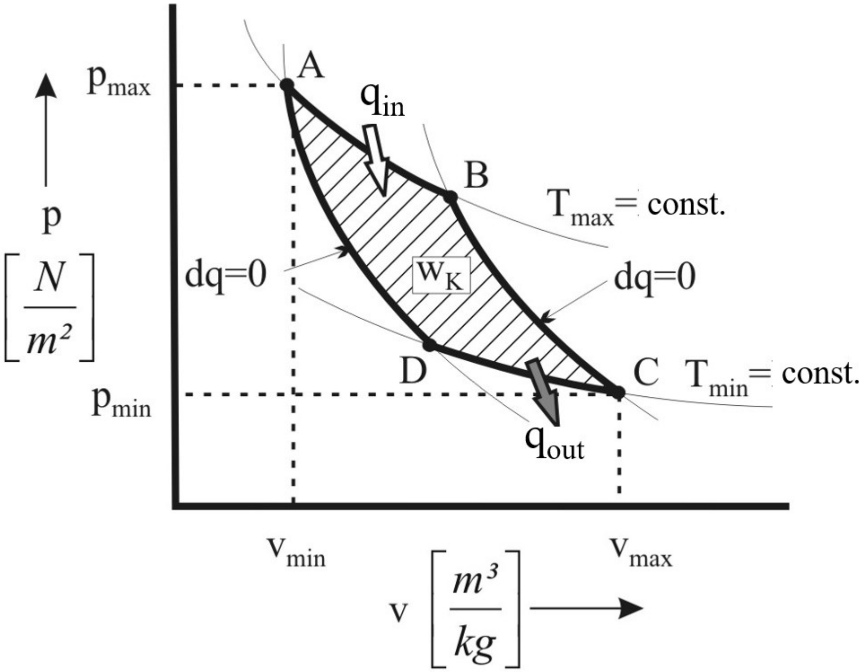

Fig. 8.11 Example of a thermodynamic cycle for producing work, thus clockwise turning – in this case with maximum thermal efficiency, as an ideal Carnot cycle

It is just as important to balance the exchanged heat and the exchanged work in the entire process: How much work does the machine do at all, how much heat should be exchanged – supplied (Q_{in}) and released (Q_{out}) - in the whole process? The ratio of the total expected work to the total heat to be invested is nothing else than a relationship between benefit and effort.

In thermodynamics, this ratio shown in Eq. (8.18) and Eq. (8.19) is defined as thermal efficiency.

The work within the thermodynamic cycle can be expressed as a sum of all exchanged heat (supplied and released), thus, the thermal efficiency depends only on the ratio of the released and the supplied heat

$$\eta_{th} = \frac{W_K}{Q_{in}} = \frac{Q_{in} + Q_{out}}{Q_{in}} = 1 + \frac{Q_{out}}{Q_{in}} \tag{8.18}$$

$$with \;\; Q_{out} = -|Q_{out}|$$

$$\eta_{th} = \frac{W_K}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \tag{8.19}$$

η_{th}	$[-]$	thermal efficiency
Q_{in}	$[J]$	heat supplied
Q_{out}	$[J]$	heat releases
W_K	$[J]$	cyclic process work

And if the pressure becomes too high for the screws, the temperature too hot for the boiler or for the piston materials, if the dimensions become gigantic or the efficiency too low, then the elementary changes of state have to be assembled in a different manner, in another thermodynamic cycle.

Equipped with such data, the machine or the function module can then be built around the process that the working fluid has to carry out!

9

The irreversibility of natural processes

9.1 Combustion is irreversible

Fire!

The fuel hisses out of the nozzle flowing through many thin holes. It becomes finely atomized, then evaporated and swirled vigorously with the oxygen from the air within the combustion chamber. The fuel-oxygen mixture ignites by itself, red and light-yellow flames are formed, the combined pairs of hydrocarbon and oxygen dance fiery waltzes, as at the Vienna Opera Ball. They increasingly burn for each other, they become a heart (of carbon) and a soul (of oxygen). The hydrogen from the fuel and the nitrogen from the air should do what they want around the couples. What or who could, out of the blue, make everything run backwards? The waltz backwards, that would be possible, dancing backwards also, some couples diverging, that´s not new. Such processes could be reversible. But tearing your heart and soul apart? Who can reform the fire swirls within a combustion chamber back to fuel droplets and to oxygen particles which will shoot back into the air and distribute there homogeneously? This is not possible as a natural process (Fig 9.1). There is an irreversible process.

Some tendencies towards reversibility are recognizable in different actions because most processes in nature have a certain elasticity: In the case of fire, some burning reactions are reversed at combustion temperatures above 2000°C. By splitting just formed carbon dioxide and water particles, among other molecules, some carbon and hydrogen atoms are formed, which occasionally find to each other, in

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_9

fractions of the initial fuel molecules. Nevertheless, a gasoline molecule, contains usually eight carbon and eighteen hydrogen atoms which are connected as a chain. Initial traces of reversibility do not determine the direction of a process.

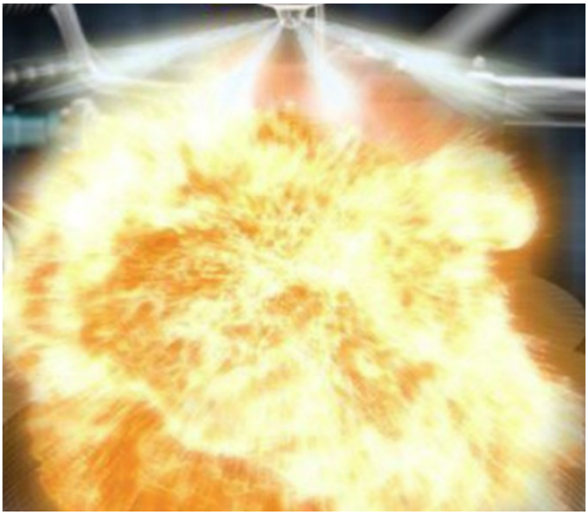

Fig 9.1 Burning process of an injected fuel with oxygen from air in a combustion chamber

Is every process in nature irreversible?

- Water flows naturally from a full vessel into an empty vessel when the latter is placed one meter lower. Is this process irreversible, or can the original state be restored? The reversal is quite possible, by means of a water pump. However, the pump needs work, for example as electrical energy from the socket.
- Air under a pressure of 6 bar can flow naturally from one chamber to another chamber, in which the air had only a pression of one bar, when a valve opens between the chambers. The original state is certainly achievable again, but this requires an air compressor which consumes energy from the environment.

Even if an original state can be restored after a change of state, this process does not always have to be reversible!

A reversibility, if even possible, don´t need energy from the environment!

Any form of irreversibility costs energy from the environment of the respective process.

The energy balance during a process must always take into account its irreversibility.

The Law on The Conservation of Energy (first law of thermodynamics, (Chapter 7) means that the total energy within an energetically insulated system remains unmodified during an arbitrary state of change, despite some possible conversion of heat in work or vice versa (Fig. 7.1).

All physical laws are bound by laws of conservation: they are valid not only in thermodynamics, but also in mechanics and in the theory of relativity.

However, the law of conservation of energy (first law of thermodynamics) does not provide any information on whether a supplied energy can be completely converted into another form during a process *(for example, heat in work).* Moreover, the direction of a natural process is never deductible from the first law.

This is like the burning process in the previous example: such an event can only run from the *fresh mixture of fuel and oxygen to carbon dioxide, water vapor and nitrogen,* but not in the opposite direction, despite some weak approaches to reversibility.

This is similar with all the balancing processes in nature:

Examples:

- pressure balance	*a flow always runs from the higher to the lower pressure.*
- temperature balance	*heat transfer always takes place from the higher to the lower temperature.*
*- concentration balance**	*molecules always move from the higher to the lower concentration.*

A natural process always proceeds in the direction of equilibrium.

A process in the opposite direction can only be carried out when an external energy is supplied, which in turn causes a change in the state of the environment.

9.2 Direction and limits of energy conversions

The conservation of energy in an entire system is described in the first law of thermodynamics.

The energy balance between heat and work, after a change of state, can also be derived from the first law by means of internal energy and enthalpy.

Nevertheless, if all the heat supplied in a process can be converted into work, or vice versa, this cannot be deducted from the first law.

For this purpose, something about the natural sequence of processes should be specified. From this necessity arose the "Second Law of Thermodynamics".

Extensive knowledge has been gained about numerous forms of natural processes over the centuries. There are some examples:

- in the course of a natural process, energy is always used in an irreversible form.
- such a process has only one natural sequence.
- an opposite sequence requires an energy input from the environment into the system.

The Second Law of Thermodynamics, like the First, was phenomenologically deducted. There are several formulations of this law, but they are compatible with each other.

Formulations of the Second Law of Thermodynamics:

Heat can never pass on its own from a system with low temperature to a system with higher temperature. (Clausius, 1822-1888)

***A process in which the conversion of the heat of a single source with constant temperature into work is not possible.* (Thompson, 1753-1814)**

***Near the equilibrium state of a homogeneous system, there are states that can never be achieved without heat exchange.* (Caratherdory, 1873-1950)**

***All processes where friction occurs are irreversible.* (Planck, 1858-1947)**

All natural processes are irreversible.* (Baehr, 1928-2014*)

Comment: A propulsion system cannot do any work if the energy (as heat) comes from a single heat source (Thompson, Caratherodory), neither in series of thermodynamic cycles nor in a single thermodynamic cycle. This is also not the case if the energy balance itself, according to the first law, is given (avoidance of the perpetual motion machine of first kind). A propulsion system in which all the heat supplied would have to be converted into work is defined as a perpetual motion machine of second kind.

If not all the heat, how much of it can be converted into work in a machine or plant?

The French physicist Sadi Carnot (1796-1832), son of Lazare Carnot, (*a major figure of the French Revolution, and even Minister of War under Napoleon Bonaparte*), established the mathematical and physical statement of the Second Law of Thermodynamics at the age of only 23 (1819).

Carnot's plan: If a heat engine cannot fully convert the heat of a single (hot) source into work, it must give some of it to a second (colder) source, but please as little as possible. In this way, the process could be restored to its original state, as the starting point of a new cyclic process.

Sadi Carnot actually wanted to make the best of it (Fig. 8.11): first absorb the heat from the hot heat source into the working medium at the maximum possible and at permanently constant temperature. Then release a very small amount of heat to the cold source from the working medium at a minimum possible and at permanently constant temperature. The working medium should not exchange any heat between the two sources:

- during the expansion from the hot to the cold source, the heat would otherwise be given away,
- during the compression from the cold to the hot source there would be no heat from the environment anyway (Fig. 9.2).

The actual usable work is generated during the expansion. However, a part of it must be invested in the following compression. The difference between the expansion and the compression work is equal to the difference between the supplied and the released heat. This corresponds to the energy balance expressed by the first law. Therefore, the usable work can never be as large as the heat supplied.

As already mentioned and as shown in Eq. (8.19), the work within the thermodynamic cycle can be expressed as a sum of all exchanged heat (supplied and released), thus, the thermal efficiency depends only on the ratio of the released and the supplied heat.

$$\eta_{th} = \frac{W_K}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \qquad (8.19)$$

η_{th}	$[-]$	thermal efficiency
Q_{in}	$[J]$	heat supplied
Q_{out}	$[J]$	heat released
W_K	$[J]$	cyclic process work

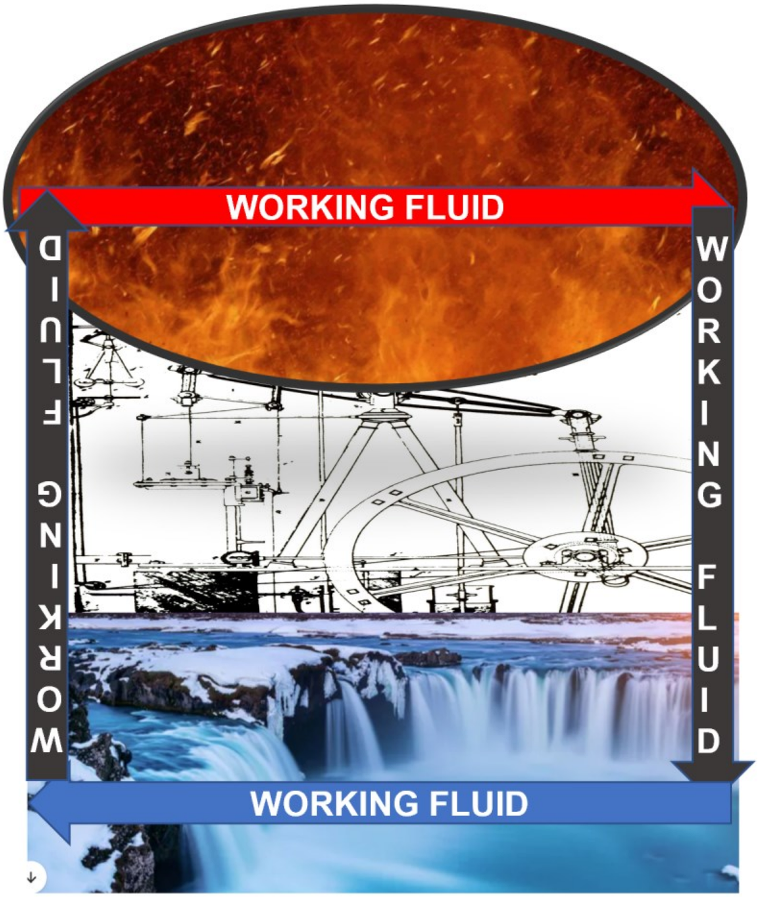

Fig. 9.2 Limits of an ideal Carnot cycle: heat supply at maximum temperature, heat release at minimum temperature, expansion and compression without heat exchange

The relationship between benefit and investment, already defined as "thermal efficiency", is again in demand in this case:

- the benefit is the work within the thermodynamic cycle, as the difference between expansion and compression work. This corresponds exactly to the difference between supplied and released heat (First Law).
- the investment consists on the supplied heat.

Thus, the thermal efficiency depends only on heat supply and heat release.

The Carnot cycle consists, as shown in (Fig. 8.11), of four elementary changes of state: two at a constant temperature and two without heat exchange (Chapter 8.2). The determination of the exchanged heat along the two changes of state, each with a constant temperature, is easily possible in base on heat capacity and temperature differences (Chapter 8.2). Last but not least – but only in the case of such an ideal Carnot cycle – only a ratio of the maximum and the minimum temperature remains.

Considering

$$\eta_{th} = \frac{W_K}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \qquad (8.19)$$

and with the relationship for state changes at constant temperature

$$q_{12} = RT ln\left(\frac{v_2}{v_1}\right) \;, \; q_{12} = RT ln\left(\frac{p_1}{p_2}\right) \qquad (8.14)$$

q_{12}	$\left[\frac{J}{kg}\right]$	specific heat exchanged from state 1 to 2
R	$\left[\frac{J}{kg\ K}\right]$	ideal gas constant (for a specific gas)
T	$[K]$	temperature
v	$\left[\frac{\mathrm{m}^3}{kg}\right]$	specific volume in a state (1 or 2)
p	$\left[\frac{N}{m^2}\right]$	pressure in a state (1 or 2)

there appears:

$$\eta_{th} = 1 - \frac{\left|mRT_{CD} ln\left(\frac{V_C}{V_D}\right)\right|}{mRT_{AB} ln\left(\frac{V_B}{V_A}\right)} \text{ for } V_C \text{ greater than } V_D \qquad (9.1)$$

m	$[kg]$	fluid mass
T	$[K]$	temperature
V	$[m^3]$	volume in a state

Taking into account the proportionality of $\frac{V_C}{V_D}$ and $\frac{V_B}{V_A}$ from the relationship between temperatures and volumes for the isentropic changes of state BC and CA the result is:

$$\eta_{thC} = 1 - \frac{T_{CD}}{T_{AB}} \rightarrow \eta_{thC} = 1 - \frac{T_{min}}{T_{max}} \qquad (9.2)\ (9.3)$$

η_{thC}	$[-]$	Carnot thermal efficiency
T	$[K]$	temperature

The thermal efficiency of an ideal Carnot cycle carried out with air depends only on the extreme temperatures during heat exchange on hot and on cold side.

The temperatures in this case are expressed in Kelvin and cannot be introduced directly in °Celsius. The following applies:

1°Celsius = (273,15 + **1**) Kelvin, or
10°Celsius = (273,15 + **10**) Kelvin,

Every developer of a promising heat engine

- without friction and losses,
- with an almost ideal working medium,
- with a thermodynamic cycle formed as a con- catenation of almost reversible elementary state changes,

should definitely pay attention to the available heat sources (the hot as well as the cold one.

Example:

- *Temperature of the hot source: 2200°C (corresponding to a very efficient combustion)*
- *Temperature of the cold source: minus 20°C (corresponding to a winter Siberian ambient air)*
- *The possible thermal efficiency of an ideal Carnot cycle between these heat sources would achieve 90%. Ten percent is thus lost simply because the working medium has to return to its original state in order to start a new cycle!*

- *If the hot source can't be as intense because the fuel can't achieve it, the maximum temperature could only be 800°C. And if the air as cold source has a temperature of 40 °C (corresponding to a summer environment in Dubai), only about 70% of thermal efficiency remains.*

If both sources had the same temperature (i.e., practically, only one source, even at 2200°C), the thermal efficiency would be ***zero*** *because there would be no work (see Thompson).*

An efficiency of 100% presupposes that the heat release would have to take place at zero Kelvin, (minus 273.15 °C), where no matter moves anymore!

A "perfect machine" is and remains an illusion because the inevitable loss of thermal efficiency is provoked exclusively from the "outside": from the fuel and from the environment!

No inventor should dream of being able to jump beyond the limits of a Carnot process. This actually runs along the borders with the environment. No other cycle, combined with elementary, ideal changes of state, can reach all these limits [1].

Nevertheless, a question is imposed: could be possible to implement a Carnot cycle at all, even if not all state changes are ideal or leastwise reversible?

This is basically possible, both with piston engines and with turbomachinery. Decisive here is the adequate steerage of the heat exchange along each change of state. The real problem is caused only by the extreme values for pressure and volumes, at the fixed temperature limits [1].

What would the implementation of a Carnot cycle based on a diesel reciprocating engine look like, even with the acceptance of irreversible processes? For this purpose, the working medium should be enclosed (never changed with environment) and the heat exchange around the cylinder, along the piston course, should be steered as follows:

- at start of compression: heat release at a minimum, constant temperature via heat exchangers to an external cold medium,

- further compression: without heat exchange up to the maximum temperature,
- then extension of the piston while maintaining the maximum temperature due to massive heat supply from an external hot medium,
- then further extension: without heat exchange until the minimum temperature is reached again.

Example:

The basic diesel engine for such readjustment to a Carnot circuit could have a displacement of 1.8 liters. The start of compression in the Carnot cycle occurs at 1 bar and 10°C. At the end of the entire compression (foremost with heat release, and subsequently without heat exchange), the pressure would achieve 5323 bar and the compression ratio would be 693 (in comparison: diesel compression ratios are in the range of 18 to 22)! No conventional material can withstand this pressure, neither in the engine nor in a heat exchanger!

Inversing the problem, trying to realize a Carnot cycle using a basic Diesel engine, not the maximum temperature, but the maximum pressure must be kept at a limit. At the same maximum pressure as in the basic diesel piston engine (75.7 bar), the maximum temperature in the Carnot cycle would achieve only 372°C instead of 2200°C and the work gained in the cycle would be very low. Moreover, the efficiency would be far below that of a common diesel engine!

Using a turbomachinery, a Carnot cycle with combustion and cooling could also be realized directly when using a working medium. The problem would remain even with such a design of the unjustifiable peak pressure, but also the execution of a turbine for the expansion, which would have to withstand continuously 2200 ° C!

9.3 Entropy as a measure of irreversibility of processes

A sensational conclusion results from the comparison of the thermal efficiency of an ideal Carnot cycle when expressed by means of heat ratio and by means of temperature ratio, respectively [1]: Both expressions are equal, thus an exchange of terms among each other is allowed: The heat supply term can be divided by the maximum temperature and, at the other hand, the heat release term ca be divided by the minimum temperature.

The sensational conclusion is: The heat supply divided by the maximum temperature is equal to the heat release divided by the minimum temperature!

It must be emphasized again that the supplied heat has a much higher amount than the released heat, and that the maximum temperature is much higher than the minimum temperature!

In other words, if you subtract the low-temperature-related (released) heat from the high-temperature-related (supplied) heat in an ideal Carnot cycle, the result is zero!

This reference of heat to the respective exchange temperature is a remarkable term: combining all the terms of this kind in an ideal thermodynamic cycle which is considered reversible, as in Carnot's cycle, the pointer of the scale shows at the end zero.

The German professor Rudolf Clausius introduced this term (heat divided by the respective exchange temperature) invented by him in 1865 with the aim to describe processes under the name entropy.

Equalizing (8.19) and (9.3) it results:

$$\frac{|Q_{out}|}{Q_{in}} = \frac{T_{min}}{T_{max}} \rightarrow \frac{|Q_{out}|}{T_{min}} = \frac{Q_{in}}{T_{max}} \rightarrow \frac{Q_{in}}{T_{max}} = \frac{|Q_{out}|}{T_{min}} \qquad (9.4)$$

Q_{in}	$[J]$	heat supplied
$\|Q_{out}\|$	$[J]$	absolute value of released heat

with a general form:

$$\frac{\Delta Q_1}{T_a} + \frac{\Delta Q_2}{T_b} = 0 \rightarrow \sum_{i=a}^{n} \frac{\Delta Q}{T_i} = 0$$

ΔQ	$[J]$	difference heat

Therefore, the entropy is expressed as:

$$S - S_0 = \int \frac{dQ}{T} \quad \left[\frac{J}{K}\right] \text{ and } S_2 - S_1 = \int_1^2 \frac{dQ}{T} \tag{9.5}$$

S	$\left[\frac{J}{K}\right]$	entropy in a state

Entropy is an artificial word based on the ancient Greek words <u>en</u> (in) and <u>trope</u> (flection). The ideal, reversible Carnot cycle was only the basis for the introduction of entropy, which very quickly invaded many areas of science, albeit, sometimes, far from its original significance!

Just because the sum of the entropies in a reversible cycle is zero,

$$\oint_{irrev} \frac{dQ}{T} = \oint_{irrev} dS = 0 \tag{9.6}$$

Clausius would certainly never have introduced this term. Entropy only becomes remarkable when a process is irreversible.

$$\oint_{irrev} \frac{dQ_E}{T} < 0 \tag{9.7}$$

$$\begin{array}{ccccc} \displaystyle\oint_{1\,irrev}^{2} \frac{dQ_E}{T} & < & \displaystyle\oint_{1\,rev}^{2} \frac{dQ_E}{T} & = & \displaystyle\oint_{1}^{2} \frac{dQ}{T} \\ \downarrow & & \downarrow \rightarrow & & \downarrow \\ dS_E & & & & dS \end{array} \tag{9.8}$$

Q_E	$[J]$	efficient heat
S_E	$\left[\frac{J}{K}\right]$	efficient entropy

Q_E means an “efficient”, thus an “utilizable” energy in form of heat, whereas Q is all the heat exchanged during the considered process.

During any natural, irreversible process, the entropy will increase, according to the relationship described by the equation (9.8).

The entropy of a system becomes greater during an irreversible change of state than the entropy, which would be caused by a utilizable energy conversion.
Reason: The pursuit of a state of equilibrium, which characterizes every natural process, is always bound to an energy dissipation.

(Formulation of the author, see [1])

$$S_2 - S_1 = \int \frac{dQ}{T} > 0 \tag{9.9}$$

In this context, entropy is a measure of the quality of an energy exchange with regard to its utilizable conversion.

This also applies to irreversible changes of state without any utilizable energy conversion. Such a process is, for example, the irreversible change of state without heat exchange, in which the entropy should not appear, but it always increases.

The difference between the change in entropy in the course of the same process in ideal and in real form is a quantitative expression of its irreversibility.

Example:

During the friction-afflicted flow of a fluid through a heat-insulated tube, its entropy increases. This can be registered as an increase of the fluid temperature or as a deceleration of flow velocity at the same pressure difference between input and output of the tube, compared to the frictionless (reversible) flow.

The increase in internal energy of the medium as a result of the temperature increase due to friction is then consumed in the natural temperature compensation between the medium and the environment – after it has been discharged from the pipe. And this heat does not benefit anyone, it only makes the environment warm!

Entropy was originally introduced as a simple pointer of the irreversibility of a state change. This should be a simple operator without an own physical meaning. Entropy can be exactly calculated, in base on the heat capacity of the working fluid and from two of the three usual state variables (pressure, temperature, volume [1].

For this purpose, the implied state variables must be known at the beginning and at the end of the respective change of state. This can be done by experimental determination (measurement).

Two concrete examples, deducted in [1]:

$$dS = c_p \frac{dT}{T} - R \frac{dp}{p} \;\rightarrow\; S_2 - S_1 = c_{pm} \ln \frac{T_2}{T_1} - R\, ln \frac{p_2}{p_1} \qquad (9.10)$$

$$dS = c_v \frac{dT}{T} - R \frac{dv}{v} \;\rightarrow\; S_2 - S_1 = c_{vm}\, ln \frac{T_2}{T_1} - R\, ln \frac{v_2}{v_1} \qquad (9.11)$$

c_P	$\left[\frac{J}{kg\ K}\right]$	specific heat capacity at constant pressure
c_V	$\left[\frac{J}{kg\ K}\right]$	specific heat capacity at constant volume
c_{pm}	$\left[\frac{J}{kg\ K}\right]$	middle specific heat capacity at constant pressure
c_{vm}	$\left[\frac{J}{kg\ K}\right]$	middle specific heat capacity at constant volume

The discrepancy between the entropy difference in the assumed ideal (reversible) course of the respective change of state and the entropy difference, which is calculated on the basis of state measurements at the beginning and end of the real state change, is a quantitative expression of irreversibility.

Basically, irreversibility is caused by dissipation and friction processes. The effect of their reduction by appropriate measures in the course of the process in a machine is quantitatively expressed by the entropy. For the development of function modules in a vehicle, the calculated entropy values are quantitative criteria for the optimization between energy consumption and implementation effort.

Being able to evaluate the irreversibility of processes in nature and technology gave entropy its own life and momentum in the scientific world!

The entity "system-environment" that has no finite limits, is to be seen as an energy-insulated system! In this case, any natural process, in which friction or balancing processes occur, is characterized by an increase in entropy.

So far so good. But the conclusion of many entropy philosophers in the world is tremendous and often dangerous as well. The starting points of such theories are intrinsically correct:

"The entropy of the entity "system-environment" is perpetually increasing as a *result* of *natural processes".*

"The energy of the world is constant, the entropy of the world strives towards a maximum".

However, in base of such postulates, in the course of the epochs, scholars of different fields of science derived theories about "the heat-death of the universe", but also about the "cold death of the universe (big freeze)", depending on the side from which the entropy and the energy was considered.

Despite such tremendous scenarios, humans with life experience should never forget:

In our world there are an infinite number of compensation potentials that cannot or must not be transformed because of given conditions or circumstances.
The spirit is given by the activation of the potentials, or, may be, by the initial splitting of cause and effect.

10

Ways from heat to work

10.1 Realizability and limits of processes in thermal machines

The conversion of heat into work in a thermal machine is fundamentally dependent on the extreme values of the temperature during heat supply and heat release in terms of quantity (performed work) and quality (thermal efficiency) within the respective process (Chapter 9.2).

For thermal engines with internal combustion (*gasoline engines, diesel engines, gas turbines*) and for thermal plants with external combustion (*powerplants, combined heat and power plants - CCGT, steam engines*) the following heat sources are usual:

- hot source: **the fire**, which is generated by the burning mixture of fuel with atmospheric oxygen. It is recommendable to drag the combustion temperature in the range of 2000°C, because at higher levels nitrogen oxides and free atoms of hydrogen or oxygen are formed and pollutants can form. In addition, if temperatures are too high, the consistency and thermal and mechanical strength of the components could be affected.
- cold source: the atmospheric air or a water flow in **the environment**. The working medium of the heat engine could certainly also be led to a very cold source by a chiller. However, the chiller itself also needs work for its cycle, which in turn costs energy!

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_10

For an efficient heat exchange between the machine and the environment, the heat capacity of the utilized working medium (*air, water, other fluids*) is decisive.

For the heat produced at the hot source, the calorific value of the fuel is authoritative.

Example:

The heating (calorific) value of hydrogen is 120 megajoules per kilogram of hydrogen, the heating (calorific) value of gasoline is "only" 44 megajoules per kilogram of gasoline.

Does hydrogen therefore create a higher temperature or more heat at the "hot source"? Neither, nor: This heating value only means that 2.7 times less kilogram of hydrogen than gasoline is needed for the same heat.

In order to generate this heat, however, a combustion of the respective fuel with air is required. But hydrogen needs 2.3 times more air than gasoline for complete combustion. Thereby the heating value of the hydrogen is "diluted" to a "mixture heating value" of 3.0 megajoules per cubic meter of mixture. This should be compared to 3.9 megajoules per cubic meter of mixture when mixing gasoline with air. The heating value of the mixture when using hydrogen is lower because in a given combustion chamber volume, the hydrogen, with its very low density, needs a lot of "space", which is wrested from the air. As a result, there is less mixture mass (kilogram of mixture) in the combustion chamber.

Other fuels such as *diesel fuel, natural gas, ethanol, methanol, rapeseed oil or palm oil* result in heating values in mixtures with air in the range of 3.3 to 4 megajoules per cubic meter of fuel/air mixture.

The heat to be expected from the combustion of a conventional fuel with air remains almost the same for the same mass of mixture, regardless of the type of fuel.

Thus, the maximum achievable temperature at a "hot source" remains almost the same whether gasoline, hydrogen or an alcohol is burned. On the other hand, the achievable minimum temperature at the "cold source" depends only on the weather in the area.

The efficiency of the energy conversion of heat into work in a machine or plant is therefore determined, within approximately equal temperature limits T_{max} - $_{min,}$ by the way in which the thermodynamic cycle is carried out.

The efficiency of such conversion can be expressed by two criteria:

- maximum specific work in the cycle (*kilojoules per kilogram of mixture*)
- maximum thermal efficiency (dimensionless) as an expression of the specific fuel consumption (kilograms per kilowatt-hour) but also the specific emissions of combustion products (kilograms or grams per kilowatt-hour).

A comparison of the possible thermodynamic cycles within the given temperature limits should first be made regardless of the type of machine in which they could be implemented.

When comparing the possible thermodynamic cycles, there often appears a conflict of objectives between the afore mentioned criteria: specific work versus thermal efficiency. The relationship between the specific work and the thermal efficiency also changes when the load requested by the machine is changed (between full load and part load).

10.2 Comparison of ideal processes for thermal machines

The realizability and limits of thermodynamic cycles for the conversion of heat into work can be evaluated on the basis of the following representative process guiding:

Carnot, Stirling, Otto, Diesel, Seiliger, Joule, Ackeret-Keller [3].

For clarity, all compared cyclic processes are considered ideal: all changes of state must be reversible, the working medium is an ideal gas, the mass and chemical structure of which initially remain unchanged throughout the entire cycle process.

Each of the mentioned cycles is considered for this comparison as a concatenation of elementary changes of state (which means at constant *pressure, temperature or volume, or without heat exchange*), whereby – regardless of their elementary form – four basic types of processes occur:

- compression,
- heat supply
- expansion,
- heat release.

For the comparison, the initial state is assumed to be the atmospheric state (1 bar, 10°C).

The following maximum temperatures as a result of the combustion of one of the mentioned fuels are taken as a basis:

- for the full load range:	1900°C
- for the partial load range:	1100°C

In order to relate the comparison to the usual gasoline and diesel engines, the mass of the working medium is derived on the basis of the same displacement volume (1.8 liters) of a piston engine (Fig. 10.1).

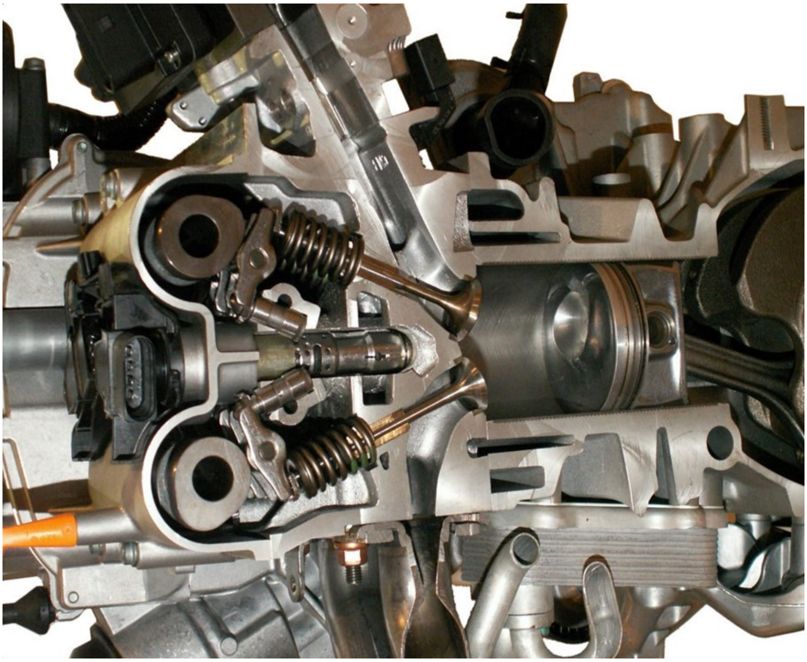

Fig. 10.1 Piston engine as a basis for the comparison of cyclic processes

From the exact calculation of the state variables for all states as well as of the heat and work exchange along each elementary change of state in the respective processes [3] in this chapter only the representative results are listed.

CARNOT–Cycle

D The ideal Carnot cycle has the advantage of the highest thermal efficiency of all cycles within the same temperature limits, which would ideally lead to the lowest fuel consumption if implemented. The Carnot cycle consists of:

1. heat supply at a constant, maximum temperature,
2. expansion without heat exchange,
3. heat release at a constant, minimum temperature,
4. compression without heat exchange.

If the process were to be implemented in a piston machine, the heat supply at the maximum constant temperature would also be associated with a simultaneous expansion. Analogously, the heat release at the minimum constant temperature is associated with a simultaneous compression.

The main results of the calculation are summarized as follows:

	full load	part load
maximum temperature	1900°C	1100°C
maximum pressure	5322 bar	607 bar
specific process work	783 kJ/kg	276 kJ/kg
thermal efficiency	87%	79%

The comments will be made in comparison with the processes described below.

STIRLING–Cycle

The Stirling process is characterized by external combustion (as under a boiler) and not by internal combustion (as in gasoline and diesel engines).

The working medium remains enclosed in the working cylinder, chemically unchanged, without being replaced in each cycle, as in gasoline and diesel engines. Stationary, external combustion has advantages in terms of combustion chamber design, process efficiency and applicable fuel types (Fig. 10.2).

Between 1960 and 1970, Stirling engines for direct drive of buses were developed by General Motors, some prototypes with Stirling engine drive with an output of 125 kW were later developed by Ford for automobiles [3]. Hydrogen served as the working medium.

Between 1971 and 1976, Philips and DAF jointly developed the prototype of a DAF bus (SB 200), powered by a Philips 4-235 Stirling engine in conjunction with an automatic transmission. The same Stirling engine type Philips 4-235 has also been adapted to power a MAN-MWM 4-658 bus.

These programs have not been followed up with regard to direct propulsion of a vehicle. A fundamental disadvantage of the external heat supply by heat exchange compared to an internal combustion is the relatively large surface of the heat exchanger and the relatively long duration of this heat exchange, whereby high-speed values or speed changes are hardly feasible.

When working at constant load and speed, as a power generator, such disadvantages have far less effect. At General Motors in 1967, an Opel Kadett was equipped with a GM Stirling engine GPU3 as a power generator with an output of 7 kW for the electric car propulsion.

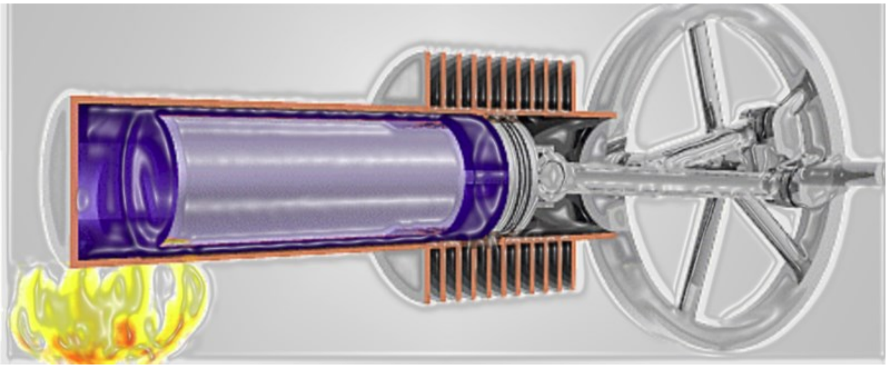

Fig. 10.2 Stirling engine – principle representation

The ideal Stirling cycle consists of two changes of state at a constant temperature and of two changes of state at a constant volume. On all these changes of state, heat is also exchanged (supplied or released), as follows:

1. <u>heat supply</u> at constant, maximum temperature and simultaneous expansion,
2. <u>expansion</u> at constant volume with heat release, which is then recuperated,
3. <u>heat release</u> at a constant, minimum temperature and simultaneous compression,
4. <u>compression</u> at constant volume with supply of recuperated heat.

Under the specified conditions with regard to temperature limits and displacement volume, the following representative results were derived:

	full load	part load
maximum temperature	1900°C	1100°C
maximum pressure	84 bar	53 bar
specific process work	1301 kJ/kg	750 kJ/kg
thermal efficiency	87% (*like Carnot*)	79% (*like Carnot*)

A potential of 70-80 °C between the warm and the cold source would already be sufficient for a useful performance of a machine working in the Stirling process. This potential corresponds to the usual difference between the temperature of the cooling water of a piston engine and the ambient temperature before the radiator. A compact, stationary Stirling engine could reduce the power loss of the driving piston engine of around 40 kW due to cooling water [3] for example, to generate electricity on board. The cooling effect of the water is made more efficient by the heat input into the Stirling process than by the classical heat exchanger in the car.

Spark-ignition engine cycle

Such cycles are realized in piston engines with internal combustion of a fuel-air mixture with ignition by means of a spark plug.

The piston stroke in the cylinder is realized via a crank drive (connecting rod and crankshaft pins). As a result, the compression stroke up to the minimum volume is equal to the expansion stroke up to the maximum volume. The ratio of the maximum to the minimum volume is called the compression ratio. This mechanism is also common for diesel engines (Fig. 10.3).

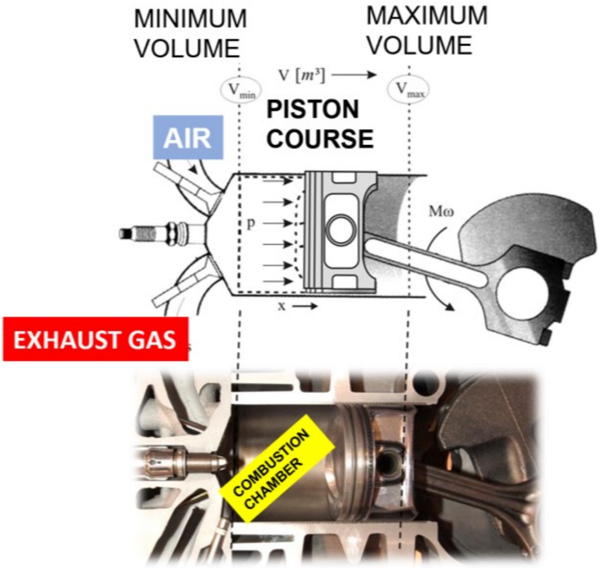

Fig. 10.3 Piston engine mechanics: Piston in cylinder, connecting rods and crankpin. Maximum volume, minimum volume (combustion chamber)

The ideal spark-ignition engine cycle consists of two changes of state at constant volume and two state changes without heat exchange:

1. heat supply at constant volume,
2. expansion without heat exchange,
3. heat release at a constant volume,
4. compression without heat exchange.

Under the specified conditions with regard to temperature limits and displacement, at a compression ratio of 12, corresponding to modern piston engines with gasoline direct injection, the following representative results were derived:

	full load	part load
maximum temperature	1900°C	1100°C
maximum pressure	92 bar	58 bar
specific process work	638 kJ/kg	275 kJ/kg
thermal efficiency	63%	63% (*like at full load*)

The efficiency of an ideal spark-ignition engine cycle depends on the purely geometric compression ratio [1].

DIESEL–Cycle

The only difference between the spark-ignition engine cycles and the diesel engine cycles (despite the almost always higher compression ratio of the diesel engine) is the type of heat supply:

1. a heat supply in the spark-ignition process at the same volume of the combustion chamber,

1. b heat supply in the diesel process at the same pressure in the combustion chamber, that means, during the piston movement towards volume increase (Fig. 10.4).

All other changes of state in spark-ignited and diesel engines are of the same type:

2. expansion without heat exchange,
3. heat release at a constant volume,
4. compression without heat exchange.

With the same initial conditions (atmospheric state), the same displacement volume and the same compression ratio, the heat supply at constant combustion chamber volume (as in the theoretical spark-ignition process) is more advantageous from the point of view of thermal efficiency compared to the heat supply at constant pressure (as in the theoretical diesel process). This means that in the real diesel cycle, the combustion process (as far as the maximum temperature can be achieved and the NO_X emission allows this temperature level) should be accelerated as far as possible. This is at the present quite feasible due to adjusted, modular split direct injection and to the controlled, concomitant self-ignition in numerous burning centers [3].

In a diesel process within comparable temperature limits, the following representative values were achieved at an assumed compression ratio $V_{max} / V_{min} = 22$:

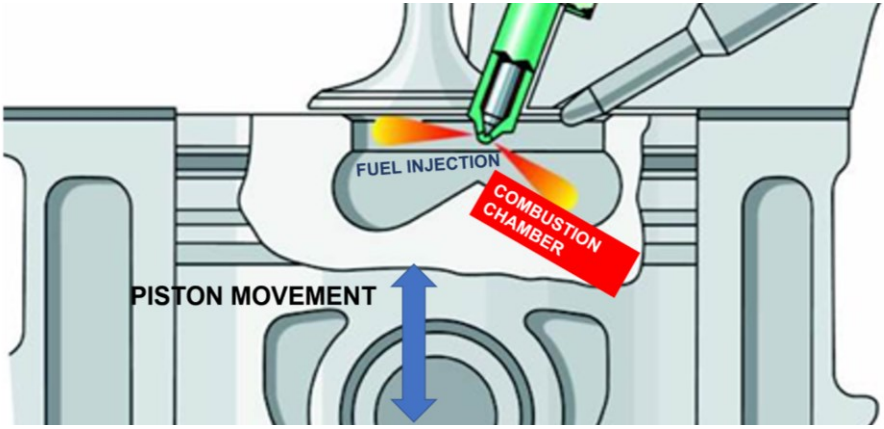

Fig. 10.4 Fuel direct injection and combustion in the combustion chamber of a diesel engine. Meanwhile, the piston moves in the direction of a volume increase (downwards)

	full load	part load
maximum temperature	1900°C	1100°C
maximum pressure	76 bar	76 bar
specific process work	783 kJ/kg	276 kJ/kg
thermal efficiency	65%	69% (*better than at full load*)

Comment: Within the engine real processes, the maximum temperature in the diesel cycle is practically higher than in the spark-ignition cycle, whereby both the efficiency and the specific process work increase.

Nevertheless, for the comparison of different process guiding forms, a comparable maximum temperature is considered to be more revealing.

SEILIGER–Cycle

In 1910, the Russian physicist Miron Seiliger introduced a comparative cycle between spark-ignition and diesel thermodynamic cycles. The purpose was to be able to better imitate the real processes using a combined heat supply, initially like the spark ignition ideal cycle, then like the diesel ideal cycle. Compression, expansion and heat release are similar to those in spark-ignition and diesel processes. The ratio of the two shares of heat supply, first at constant volume, then at constant pressure can theoretically be chosen arbitrarily. In practice, an approach to the respective real process is sought.

For the process calculation in this chapter, a combined heat supply with 30% at same volume and with 70% at same pressure is used. The compression ratio of 12 corresponds to that previously chosen for the spark-ignition process.

The following values have been calculated:

	full load	part load
maximum temperature	1900°C	1100°C
maximum pressure	55 bar	42 bar
specific process work	756 kJ/kg	334 kJ/kg
thermal efficiency	61%	61% (*like at full load*)

Comments:

The specific work lies in the range between the spark-ignition and diesel cycles.

However, it is noteworthy that within the temperature limits considered, the Seiliger cycle has a lower thermal efficiency both as the spark-ignition process and as the diesel process.

This fact is quite explainable:

- compared to the spark-ignition process, there is an isobaric proportion of the heat input at the same compression ratio, which impairs thermal efficiency.
- compared to the diesel process, the compression ratio is clearly lower, which in turn negatively affects the thermal efficiency.

For the sake of high thermal efficiency, a piston engine should achieve compression like a diesel and combustion like a gasoline engine.

JOULE–Cycle

Joule cycles are usually implemented in gas turbines (turbomachinery). So far, these have mostly been used in aircraft, but show a lot of potential for use as power generators in cars and trucks with electric propulsion and in large ships.

The difference between a gas turbine and a piston engine is considerable: each piston engine, whether with spark-ignition or diesel, first sucks in air from the environment and compresses it in the cylinder, by the piston movement versus cylinder head. At the point where the piston and the head are closest to each other, together they form a combustion chamber that is quite unfavorable for a firing: crushing height, too much width, corners and edges for valve pockets, thus, too small gaps for flame penetration at the outermost edges. And in such a squashed chamber, the fuel must be firstly injected, then atomized, evaporated, mixed with air at high pressure in an extremely short time, and also burned. The piston is then pushed by the fire pressure towards the point where the air intake had begun. The burnt gas would still have enough pressure upon the piston to expand more. But its course is limited by the conjunction with connecting rod and crank: the course during compression is thus the same as the course during expansion. The piston thus forms by its movement, one after the other, first a compressor, then a combustion chamber, and then an expansion machine. In such a simple compressor, with a very unfavorably shaped combustion chamber and with an expansion machine that does not allow a sufficient course, not all process sequences of a thermodynamic cycle can be efficiently realized.

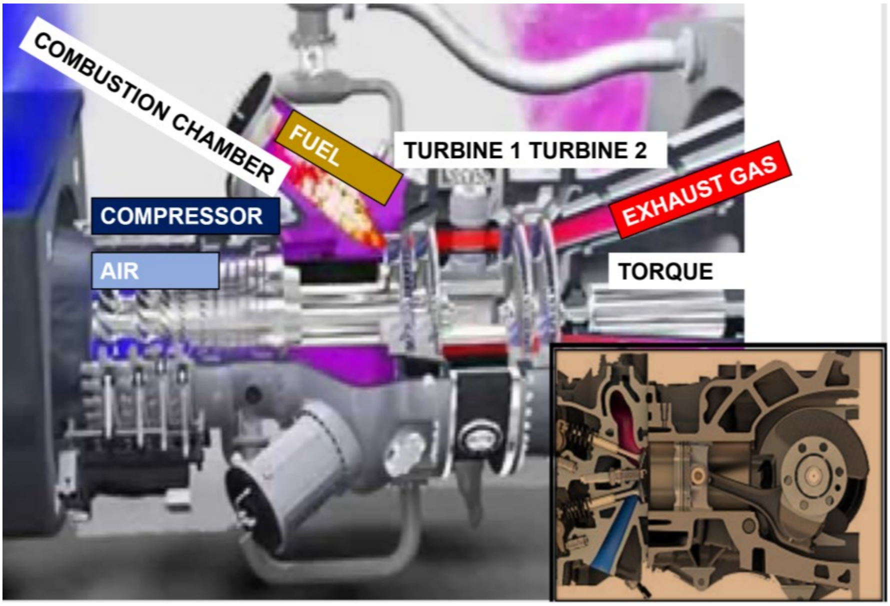

Fig. 10.5 Modules for compression, combustion and expansion in a gas turbine compared to the single chamber in a piston engine for all these process sections

In a gas turbine, on the other hand, each of these process sequences has its own space (Fig. 10.5). The compression takes place in a compressor designed precisely for this purpose, the combustion in a combustion chamber specially designed for a good firing, the expansion in a module in which the pressure of the burned gas can be relaxed up to the atmospheric pressure. However, this presupposes that all the processes take place simultaneously, not one after the other, as within piston machines. For this aim, it is no longer possible to pass an air mass through one "department", then through the other. Therefore, a mass flow is required in the gas turbine. This is usually generated as a steady stream through the machine. The air current through the compressor meet the fuel jet injected continuously in the combustion chamber becoming burnt gas that constantly turns a turbine. For such a steady flow through compressor and turbine, rotating machines are as good as the only realistic and efficient solution. Within the compressor rotor-stator pairs gradually increases the air pressure. For higher air pressure, the number of rotor-stator pairs can be augmented.

The main advantage of a gas turbine compared to a piston engine is the combustion chamber. The continuously injected fuel jet cannot reach any combustion chamber wall: if the jet is too long, the chamber can also be prolonged. The time for atomization and evaporation of the jet is not a problem because the jet flow is continually

It resembles the jet and furthermore the flame from a welding torch. And furthermore: The expansion can take place in so many turbine stages until the gas reaches the ambient pressure, so its energy is used much more than in a piston engine.

The ideal Joule cycle consists, according to these explanations, of two pairs of changes of state: one pair of them with heat exchange at constant pressure and another pair without heat exchange, as follows:

1. heat supply at constant pressure,

2. expansion without heat exchange,

3. heat release at constant pressure,

4. compression without heat exchange.

The energy of the burned gases during the expansion in the multistage turbine is used in two forms: a part of this energy is sent via a rigid axle to the compressor, which requires compression work. The remaining turbine energy is that, what is actually expected from the machine: work that generates torque. This torque can be transmitted to a propeller or to a fan that drives an aircraft through the air, or to drive a power generator, as in the propulsion systems of a modern ship. In an automobile, this moment can simply be directed to the wheels. The latter approach has always fascinated automotive engineers!

Rover introduced gas turbines for the direct propulsion of automobiles in 1950 with the car model J1. The drive had 74 kW (100 hp) with a turbine that ran at 26 thousand revolutions per minute. The car equipped with this drive reached a speed of 136 km/h. The following model, two years later, reached 169 kW (230 hp) and 243.5 km/h. This was followed by the models T3 (1956) with all-wheel drive and T4 (1961) with front-wheel drive, followed by the BRM Type 00 (1963) [3].

FIAT introduced the “Turbina” model in 1954, which had a gas turbine with 221 kW (300 hp) and was powered by kerosene. The vehicle reached a maximum speed of 250 km/h!

Chrysler presented in 1954 the model Plymouth Sport Coupé, powered by a gas turbine and of which 75 vehicles were built. This was followed in 1963 by the Chrysler Turbine Car model, with a fourth-generation gas turbine that reached 96 kW (130 hp).

But the fuel consumption was substantial: 16 to 17 liters of gasoline per hundred kilometers. Where is the problem when all processes are running optimally? The explanation is simple: a gas turbine for direct propulsion of the car wheels does not agree with a steep load change and a tremendous speed change from 1000 to 8000 rpm, as in a piston engine. The reason is that the blades of the compressors and turbines have well defined profiles and a well calculated orientation angles, which should be adjusted in all stages in the event of a change in load and speed: but this would hardly be feasible [3].

Much more interesting for future propulsion is the use of turbomachinery as a power generator on board of an automobile, i.e. as an energy source for propulsion by means of an electric motor. Such hybrid propulsion systems have already been successfully tested in some interesting prototypes around the world.

The gas turbine should do undisturbed that, what it does as best: work at a constant load and speed. No connection with the drive wheels, but only with the power generator, which supplies the electrical energy of one or more electric motors that turn the wheels.

An excellent version of this concept is the Jaguar C-X 75, which was presented in 2010 (Fig. 10.6): four drive motors with a total output of 580 kW (789 hp), acceleration in 3.4 seconds from 0 to 100 km/h. And not with 16 to 17 liters of gasoline per 100 kilometers, but with only 4.3 liters [3]!

Fig. 10.6 Jaguar C-X 75 with two gas turbines for power generation on board and four electric motors (one per wheel) for propulsion

For comparison with the processes in gasoline and diesel piston engines, an ideal Joule cycle was constructed between the same extreme temperatures [3]. As a basis, the environmental state is considered as in the previous cycle processes. The mass flow of the working medium corresponds to the air mass in the diesel engine with the displacement of 1.8 liters at a speed of 3000 revolutions per minute.

As in the diesel process, the part load in the Joule cycle is realized by reducing the heat supply at the same pressure.

A significant difference to the diesel cycle – apart from the fact that compression, expansion and heat supply take place following similar elementary state changes – is the heat release at the same, usually atmospheric pressure. This leads to the main advantage of expanding the working medium up to the ambient pressure. Differently, in both diesel and spark ignition piston engines, heat release takes place at a same volume due to the crank drive with unchanged geometry.

The Joule cycle therefore has a fundamental advantage over a piston engine process: this consist of the complete gas expansion, and thus of an increased specific work, as far as the compression ratios would be comparable. However, this is not the case in conventional gas turbines. For the comparison, a ratio with the value 7:1 between the maximum and the minimum process pressure was chosen, corresponding to the compression at a rather low geometric compression ratio in a piston engine (which cannot be explicitly expressed because of the mass flow in a gas turbine).

<u>Note:</u> The pressure ratio in the diesel process mentioned earlier was not 7, but 76!

In the ideal Joule cycle calculated as a comparison, the following values were achieved:

	full load	part load
maximum temperature	1900°C	1100°C
maximum pressure	7 bar	7 bar
specific process work	720 kJ/kg	275 kJ/kg
thermal efficiency	43%	43% (*like at full load*)

<u>Comments</u>:

Despite the considerably lower compression than in the diesel cycle, the specific process work in the turbomachinery is completely comparable to that in a diesel engine at full load (720 kJ/kg compared with 783 kJ/kg). This can be explained by the expansion of the working medium up to the ambient pressure.

In general, however, the mass flow through a gas turbine is higher than the comparative value derived from the working mass in the diesel engine with a displacement of 1.8 liters. This is possible due to the generally higher achievable speeds in the gas turbine. This leads to considerable performance values, as with the Jaguar drive quoted earlier, with very compact dimensions of the gas turbines.

ACKERET–KELLER–Cycle

The The Ackeret-Keller cycle (also known as the Ericsson cycle) is generally regarded as an ideal comparison process for power plants. Sein potential is promising on the basis of the Joule cycle described above.

The main difference between a Joule and a Ackeret-Keller (Ericsson) cycle consists only in the compression and expansion, which no longer takes place without heat exchange, but with a particularly intensive heat exchange (idealized as an extreme case, at the same temperature):

1. heat supply at constant pressure,
2. Expansion with heat supply (*from recuperation from compression with heat dissipation*) at a constant maximum temperature,
3. heat release at constant pressure,
4. Compression with heat release (*which is recuperated for the relief phase*) at a constant minimum temperature.

Between the state changes at the same extreme temperatures T_{max} and T_{min} and those at minimum and maximum pressure, a cycle is created that *(just like the Carnot cycle and the Stirling cycle)* uses the "hot source" and the "cold source" continuously at a constant temperature. The difference to the other two cycles consists only in the two different changes of state: Stirling at the same volume, Carnot without heat exchange (Ackerett-Keller at the same pressure).

As soon as the heat release during compression is recuperated for the expansion sequence, the thermal efficiency of all 3 cycles remains the same!

In the ideal Ackerett-Keller cycle calculated as a comparison, the following values were determined:

	full load	part load
maximum temperature	1900°C	1100°C
maximum pressure	7 bar	7 bar
specific process work	1056 kJ/kg	609 kJ/kg
thermal efficiency	87% (*like Carnot and Stirling*)	79%

As expected, comparable values also appear in the specific work due to a similar heat balance with the Stirling process. Both thus exceed the values of the specific work in the Joule cycle.

As a result, the Ackeret-Keller (Ericsson) cycle has clear advantages over the Joule cycle in a fluid flow engine, both in terms of the achievable specific work and of thermal efficiency.

However, the practical implementation of such a cycle is not possible due to the enormous heat exchange required during expansion and during compression: The heat exchangers would simply be giant in both cases.

In large power plants, is increasingly implemented a step-by-step approach to the ideal Ackerett-Keller cycle (not with ideal air but with water as working medium) by stepped cooling during the desired compression at a constant minimum temperature or by stepped heat supply during the desired expansion at a constant maximum temperature.

In the case of turbomachinery in aeronautical engineering, such techniques are occasionally implemented, even if only in one stage at a time:

- in the case of compression: intermediate cooling at constant pressure in the compressor, by direct water injection into the air flow,
- in the case of expansion: post-combustion of fuel during the expansion between the turbines or between turbine and nozzle.

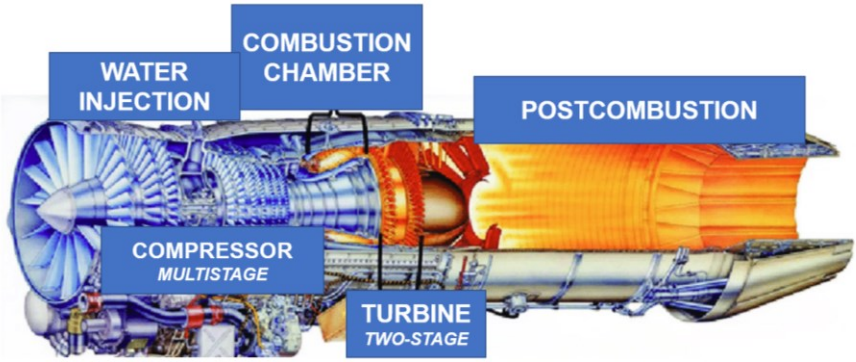

Fig. 10.7 Turbomachine with intermediate cooling in the compressor and post-combustion between turbine and nozzle (background template: GKN Aerospace Systems)

… and if water instead of fuel is injected into both the combustion chamber and the afterburner ramp (Fig. 10.7), the thermodynamic cycle turns completely upside down: heat release after compression, then expansion with intermediate cooling leads to a temperature behind the exhaust tube that is far below the ambient temperature. The air during suction is warmer, which means that the cycle is symbolically closed by a heat supply. In this case, the specific work difference between compressor and turbine would have to be secured by an electric motor.

The whole issue results in a huge air conditioning system: The machine sucks air at 40°C and reject air with water vapor at 10 to 18°C!

Let's keep all the military jets in the world on the ground and replace fire with water for the people which need cool heads!

11

Heat transfer

11.1 The three ways of heat transfer

Fire and flame!

The flame is the burning and luminous soul of the glowing fire body (Fig. 11.1).

From an engineering point of view, however, the definition of the flame is rather sobering
(see Chapter 1.2, 1.3):

A flame is a gas mixture during a combustion process.

Fig. 11.1 Fire and flame

The flames are divided into "luminous" and "non-luminous":

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_11

Non-luminous flames, which are generated, for example, during the combustion of hydrogen and carbon monoxide, have a negligible radiation intensity (watts per cubic meter).

Luminous flames. Although the emission of individual glowing particles (*e.g. carbon*) is low, a very high radiation intensity is achieved by the large number of these extremely small particles, with diameters of around 0.003 millimeters. Therefore, the flame radiation decisively determines the heat transfers in combustion chambers of all kinds.

However, radiation is not the only way of heat transfer.

Heat transfer generally occurs when there is a temperature difference, from higher to lower temperature, according to any natural balancing process (second law of thermodynamics).

The three basic types of heat transfer are the following [1]:

- heat conduction,
- heat convection (also known as convective heat transfer),
- heat radiation.

These forms usually appear together during any heat transfer.

Heat conduction occurs during a direct, physical contact between two bodies and have no movement to each other. Heat conduction in liquids and gases requires thin layers that cannot circulate. A macroscopically measured temperature corresponds to the mean kinetic energy of the particles on a microscopic scale. Particles in two bodies in direct contact that have different temperatures also have different kinetic energies. Collisions between the particles balance the energy between the two bodies and thereby, on a macroscopic scale, the temperature. Externally, no mass transport is perceived. The temperature compensation counts as heat transfer (Fig. 11.2).

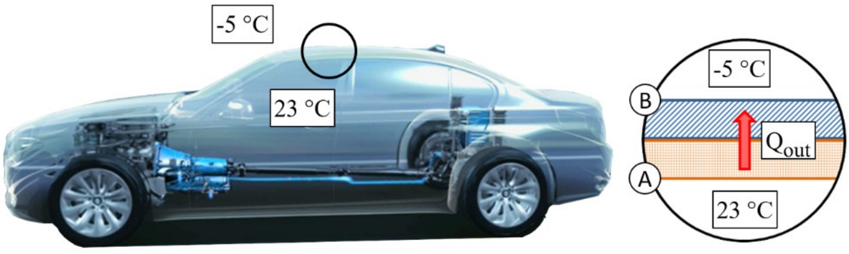

Fig. 11.2 Heat conduction through the material layers of an automotive roof between the warm interior and the cold environment

In liquid and gaseous substances that are not present in thin layers, heat transfer usually creates a *flow* that no longer corresponds to the model of heat conduction due to mass transport.

<u>Convection (a convective heat transfer)</u> occurs as energy transport with a macroscopic movement of mass particles between the substances involved. This type of heat transfer therefore presupposes a *relative speed* between the bodies involved in addition to the *mass contact*.

This model corresponds to the heat transfer between *solid/liquid* or *liquid/gaseous* or *solid/gaseous* media when at least one of the media involved acts as a *flow*. At the boundary between the two media (*in the case of a lower temperature of the flowing fluid*), the passing particles absorb energy, which is then transferred to the entire mass of the flowing medium (Fig. 11.3).

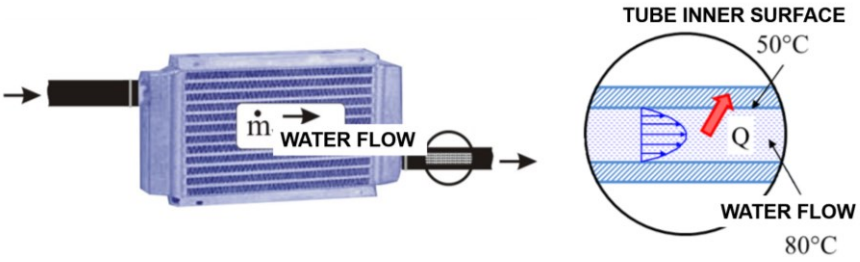

Fig. 11.3 Convection between the flowing cooling water and the inner surface of the pipeline in a cooling circuit

<u>Heat radiation</u> is characterized by heat transfer *without mass contact* between the systems involved. The heat is transported by *photons*, in

the form of *electromagnetic waves*. The classic example of heat radiation is the transfer of heat from the sun to the earth. In principle, due to its temperature, each body emits electromagnetic waves, which are converted into internal energy when received by a lower temperature body.

Example:

The heat radiation between a vehicle body and its surroundings (Fig. 11.4):

The sun radiates heat through the vacuum in space, then further through the air in the atmosphere, which also hits the roof of an automobile body. On the other hand, the air in the atmosphere is cold on the day (for example, minus 5°C). In the car, the air is warm (for example, plus 23°C) thanks also to the interior heating. This heat is at first transferred via the material of the body then pass through to the interior of the vehicle, and finally to a lesser extent radiated over the exterior surface of the body into the environment, in all directions.

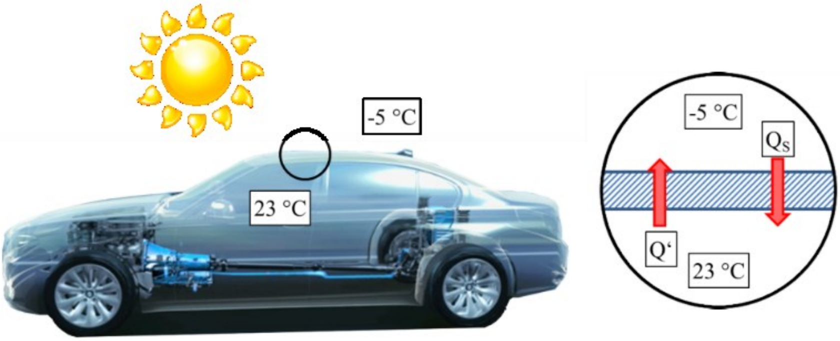

Fig. 11.4 Heat radiation from the sun onto a car body and from this body into a cooler environment

Numerous criteria and formulas have been developed for the design and evaluation of heat conduction, convection and radiation. Often in the textbooks, the criteria and definitions for heat conduction differ from those for convection, and these from those for radiation. This has to do with the respective professionals specialized in one direction or another in the course of the last century. However, one thing is a fact: all three forms occur together in most heat transfers. Therefore, they can also be set to common denominators, which is also possible by appropriate derivatives [1].

For heat conduction, convection and radiation, three common evaluation criteria can be derived:

The heat flow, as heat that is transferred per unit of time. According to the units of measurement (joules per second), the heat flow corresponds to a power (watts).

$$\dot{Q} = \frac{dQ}{d\tau} \xrightarrow{stationär} \dot{Q} = \frac{Q}{\tau} \quad \left[\frac{J}{s} = W\right] \tag{11.1}$$

$\dot{Q}$	$[W]$	energy flux (heat flux, heat flow)
Q	$[J]$	heat
τ	$[s\,;h]$	time

The heat flux density is defined as heat flow per passage surface (watts per square meter).

$$\dot{q} = \frac{\dot{Q}}{A} \quad \left[\frac{W}{m^2}\right] \tag{11.2}$$

$\dot{q}$	$\left[\frac{W}{m^2}\right]$	energy flux density (heat flux density)
A	$[m^2]$	surface

Thermal resistance is defined as a temperature gradient in relation to the heat flow.

$$R = \frac{dT}{\dot{Q}} \quad \left[\frac{K}{W}\right] \tag{11.3}$$

R	$\left[\frac{J}{kg\,K}\right]$	ideal gas constant (for a specific gas)
T	$[K]$	temperature

This is analogous to the processes and definitions in electrical engineering: The electrical resistance results from the ratio of the voltage to the current.

11.2 Heat conduction

Joseph Fourier (1768–1830) is often cited as one of the drivers of the French Revolution, then as one of Napoleon Bonaparte's companions. As a mathematician, he was also responsible for his Fourier series, as a physicist for frequency analysis and as a thermodynamicist known for the spread of heat in solid bodies. In the "Analytical Theory of Heat" (1822) he established a connection between the heat flow through a solid, straight, single-layer wall, the temperature difference between the outside and inside, and the thickness and surface of the wall.

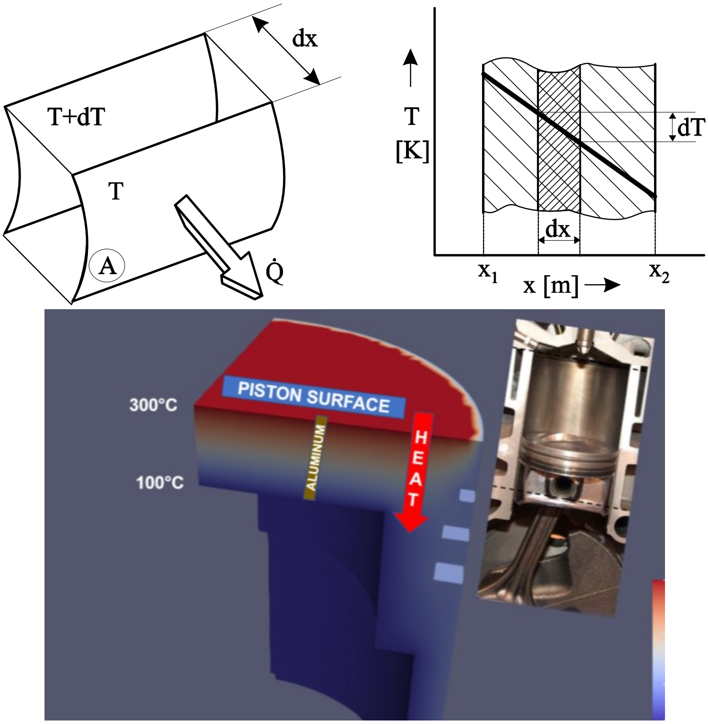

Fig. 11.5 Heat conduction through the straight, single-layer bottom of a piston in a fired internal combustion engine

These connections were so far clear, but the result changed as long as the wall was not made of wood, but of concrete or steel. But that's how the best phenomenological laws come about. Fourier also introduced a material-specific factor, whereby the equation he created achieved its correctness for all combinations: The wall could then be made of wood or brick, three centimeters or one meter thick, occupy two square centimeters or five square meters, the temperature difference between inside and outside could be 1°C or 100°C (Fig. 11.5).

$$\dot{Q} = -\lambda A \cdot \frac{dT}{dx} \tag{11.4}$$

λ	$\left[\frac{W}{m\,K}\right]$	thermal conductivity
x	$[m\,;mm]$	distance

The material-specific factor was called "thermal conductivity".

Examples of the thermal conductivity of different substances (in watts per meter and Kelvin):

Gases	→	*0,02...0,1*
Wood	→	*0,13*
Water	→	*0,6*
Steel	→	*33...52 (as a function of temperature)*
Copper	→	*370*
Silver	→	*418*

Thermal insulation is best achieved with gases. However, a gas layer that is too thick hardly fulfills this purpose: Beyond a certain thickness of the layer, a convection flow usually occurs, which intensively transports the heat between the warm and cold walls.

Therefore, porous substances (with sponge, foam or cotton wool-like structure) are suitable for thermal insulation, which on the one hand contain air in the pores and on the other hand prevent air movement.

Based on the Fourier equation, the heat flow, the heat flux density and the thermal resistance can be calculated as a result of heat conduction through single-layer and multi-layer walls made of different materials and with any shapes [1] (Fig. 11.6).

$$\dot{Q} = \frac{2\pi l(T_1 - T_{n+1})}{\frac{1}{\lambda_1}\ln\frac{r_2}{r_1} + \frac{1}{\lambda_2} ln\frac{r_3}{r_2} + \dots + \frac{1}{\lambda_n} ln\frac{r_{n+1}}{r_n}} \tag{11.5}$$

l	$[m\,;mm]$	distance
r	$[m\,;mm]$	radius

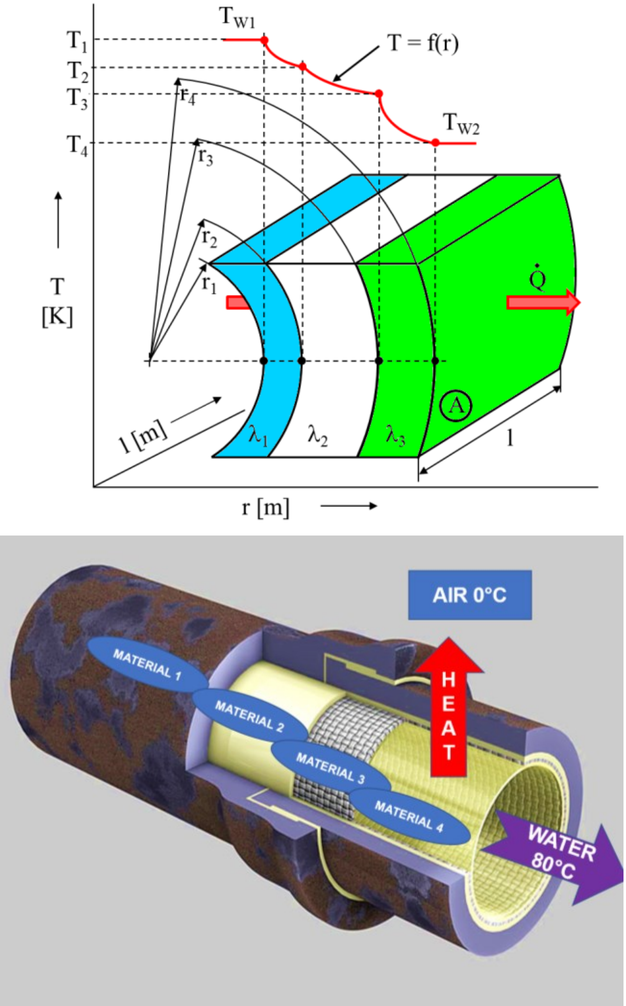

Fig. 11.6 Heat conduction through a multi-layer pipe wall

Example of heat conduction [1]:

Through a 3 mm thick sheet metal wall with an area of 0.7 m^2, heat flows from a room with an air temperature of 9°C into the environment with an air temperature of minus 7°C.

If the sheet metal wall is made of steel, the heat flow is 220 kW. However, if it is made of aluminum, the continuous heat flow quadruples.

If a steel sheet metal wall with the same dimensions is insulated with glass wool (20 mm thick) and provided with an aluminum outer jacket, the heat flow between the same temperatures drops to only 0.02 kW.

11.3 Heat convection

Convection is characterized by a relative velocity between the heat-exchanging media. The most common use case concerns the heat exchange between a flowing fluid (*liquid or gas*) and a solid wall.

In respect to the flow formation, two types of convection are defined:

- *free convection* - the flow is created as a compensation of different fluid densities. The cause of the density difference is the heat exchange itself, as between two window panes, which are several millimeters apart from each other.
- *forced convection* - the flow is specifically generated by means of a pump or a fan. In this case, the flow itself is the cause of a certain heat exchange process.

The evaluation parameters of convection are, as in the case of heat conduction, heat flow, heat flux density and thermal resistance.

The calculation of the parameters seems to be easier in the case of convection than in the case of heat conduction: The heat flow can be obtained by multiplying the heat-flowing surface by the temperature difference between the inside and the outside and by a factor (heat transfer coefficient).

$$\dot{Q} = \alpha A \left(T_f - T_W\right) \tag{11.6}$$

α	$\left[\frac{W}{m^2\,K}\right]$	heat transfer coefficient
T_f	$[K]$	temperature of fluid
T_w	$[K]$	temperature of wall

The problem is the heat transfer coefficient, which is by far not just a material property, as in heat conduction (thermal conductivity). Sir Isaac Newton (1642-1726), an English mathematician, physicist, astronomer and philosopher who introduced the first form of this complex factor around the year 1700, first dealt with this.

The heat transfer coefficient depends on the velocity, the type of flow (turbulent or laminar) and the material properties of the flowing medium. In addition, the size, shape and roughness of the fixed contact surface (wall) are important.

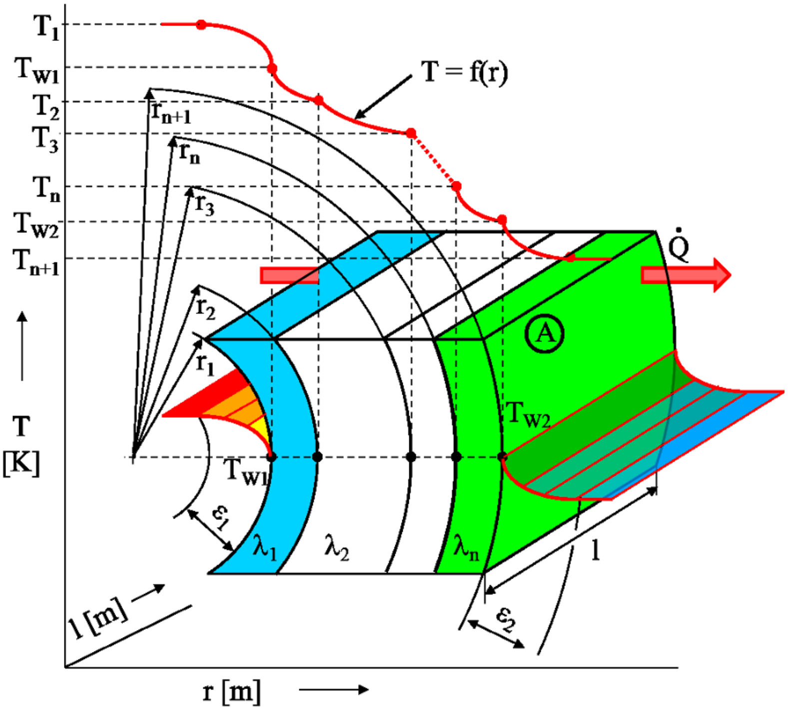

Fig. 11.7 Heat conduction through a multi-layer pipe wall

The value of the heat transfer coefficient outside a boundary layer near the wall generally corresponds to a specific situation of heat transfer. A transfer to other practical cases is only allowed if there is a similarity between the thermodynamic and fluid mechanical processes.

Nevertheless, in the case of an already built plant, it is particularly important to know how the heat transfer changes when a diameter, pipe length, inlet temperature or flow velocity is changed for any reason. It is extremely difficult to measure every new parameter configuration at every time for reasons of time and personnel.

It is therefore necessary to specify the conditions for the extrapolation of experimentally acquired knowledge from a model.

The method that allows modeling on the basis of experimentally obtained data for application in processes other than the measured ones is called similarity theory [1].

Geometric similarity is the first and simplest similarity criterion for two plants in which certain processes are to be compared. For example, the flow around a car body is often derived from experiments using a similar model on a smaller scale.

The similarity theory with regard to convection was essentially developed by the German professor Wilhelm Nusselt (1882-1957) and is expressed in the case of convection by means of a "Nusselt number". The formulas for the heat transfer were changed in such a way that the specific characteristics remain without dimensions. In processes that are thermodynamic and aerodynamically similar, these specific characteristics remain unchanged as similarity criteria. The Nusselt number, for its part, depends on other dimensionless similarity criteria based on experiments with a variety of combinations (*dimensions, velocities, type of flow, type of fluid, and other* [1]). These are the similarity numbers of Reynolds, Péclet, Prandtl, Grashof and Rayleigh.

Knowledge of the convection processes is used in particular, but not exclusively, for the design of heat exchangers.

Heat exchangers are crossed by two or more fluids between which the heat exchange takes place. The heat exchangers are generally classified according to the fluid whose heat absorption or release is of interest. Heat exchangers with two flowing media separated by the walls of the heat exchanger are notedly common.

There are heat exchangers with direct flow (*both fluids flow in the same direction*), with counterflow (*the flow directions are opposite*) and with cross flow.

Along a heat exchanger with *direct flow,* the temperature distribution is very uneven. Due to the *counterflow,* a constant temperature difference can be achieved along the heat exchanger.

The parameters of the heat exchanger with *cross-flow* (Fig. 11.8) lie between the values of the first two models.

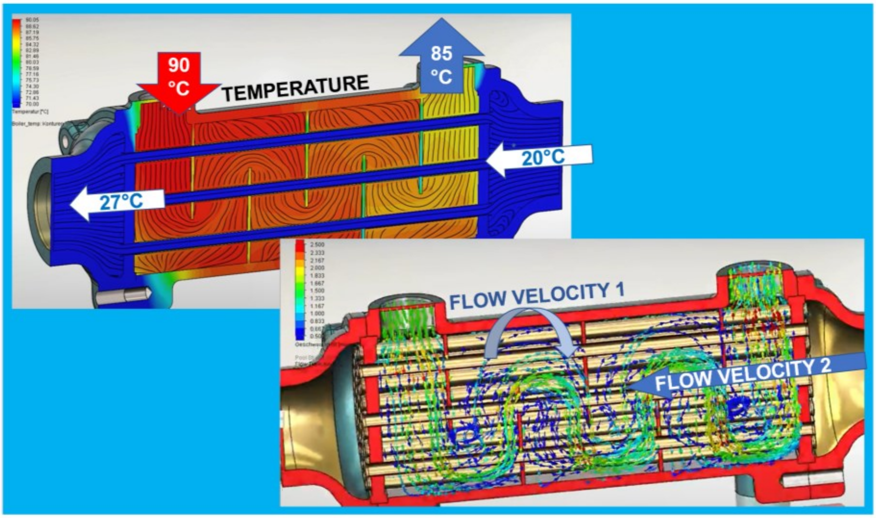

Fig. 11.8 Heat exchangers with cross-flow: Temperature and velocity distribution of the flows in the primary and secondary circuits

Example for the calculation of convection in a simple case [1]:

In a heating pipe with a length of 4 meters and an inner diameter of 12.7 millimeters, water flows at an average temperature of 80 °C. The flow velocity is 1 meter per second. The average wall temperature of the pipe is 50 °C. To calculate the heat flow from the water to the pipe wall for each 1-meter pipe length, the following procedure is used:

Determination of the heat transfer coefficient: first the Reynolds number, then the Prandtl number. For the given case of a liquid flow through a pipe, there is a formula in accessible physical tables in which the Nusselt number is expressed using the Reynolds and Prandtl numbers. With the Nusselt number and based on two other properties (pipe diameter and thermal conductivity of the water), the heat transfer coefficient is now calculated. This is used in Newton's equation mentioned at the beginning. The result: The heat flow in this case is 8.72 kW. However, if the flow velocity becomes much lower (0.05 instead of 1 meter per second), you have to handle everything again according to the same scheme. You can't just say that the heat flow is then proportionally lower, thus only 5% of the first value! In this case, the flow is no longer turbulent, but laminar. Different formulas apply, with different ranges of equations. The result may be astonishing: the heat flow is only 0.28 kW instead of 8.72 kW!

11.4 Heat radiation

Heat radiation is a form of energy transfer that does not require direct contact between the exchange systems. However, their intensity depends on the substance of both systems as well as on the substance of the intermediate medium. However, radiation is mainly dependent on the temperatures of the radiant bodies.

Radiation is an energy transport that is realized by means of electromagnetic waves. These waves arise from the movements in the molecular range due to the internal energy of the system and are emitted by the system to the outside. The higher the internal energy of the system, the greater the intensity (amplitude and frequency) of the electromagnetic waves emitted into the environment. If these waves are absorbed by another system, the kinetic energy of its molecules changes, which is registered as a temperature change [1].

A wave itself is therefore not "warm", but its effect is a warming. From this it is deduced that heat transfer between two systems that are not in direct contact is possible by conversion into and of electromagnetic energy. Like any oscillation, an electromagnetic oscillation is characterized by its frequency, or by its wavelength – as a reciprocal of the frequency at a constant transmission speed (speed of light, 300,000 kilometers per second) (Fig. 11.9).

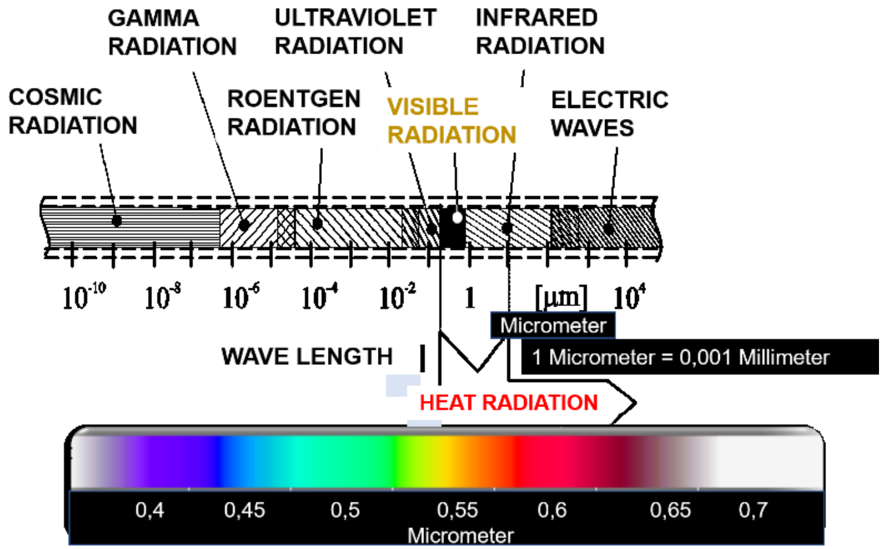

Fig. 11.9 Emission spectrum of radiation by means of electromagnetic waves

All radiation – including heat radiation – is emitted on all wavelengths, i.e. simultaneously as gamma, X-ray and infrared radiation.

However, most of the energy emitted by the heat radiation is in the wavelength range between 0.00035-0.01 millimeters. This is a "selective distribution".

Within this range, the light radiation is between 0.00035 and 0.00075 millimeters.

Examples:
Selective distribution of energy radiation by wavelength ranges [1]:

- *Of the total energy of an incandescent lamp (thread temperature: 2700 °C to 3000 °C), around 88% is emitted as light energy and 12% in the invisible infrared range of heat radiation. In the case of solar energy sent to Earth, the ratio between visible and invisible thermal radiation is 70% to 30%.*

- *Glass is permeable to electromagnetic waves in the visible wavelength range, but not to infrared wavelengths. The sun's rays, which enter a room through a window glass, transfer part of their* *energy to those objects in the room that have a lower temperature. This energy output causes a proportional reduction of the wave energy and consequently the shift of the wavelengths of the electromagnetic waves towards the infrared range. However, the waves reflected on such wavelengths can no longer cross the glass panes and are pushed back into space. This explains the temperature increase of a room as a result of solar radiation through closed windows. Similarly, the greenhouse effect in the atmosphere can be explained.*

- *Conversely, the increase in temperature of a body results in a reduction in wavelengths (the increase in internal energy causes the frequency increase of electromagnetic waves). This change runs from infrared to the visible range. For example, the "annealing" of a metal can be explained in this mode.*

Every material system, depending on its temperature, is a source of thermal radiation. It emits heat into the environment or to a neighboring system even if its temperature is lower than that of the environment or the neighboring system. This fact does not contradict the Second Law of Thermodynamics, according to which heat can only pass from the higher temperature system to the lower temperature system: the lower temperature system also sends energy, in all directions, including the higher temperature system. The direction and amount of the global heat transfer results as a balance in this exchange process (Fig. 11.10).

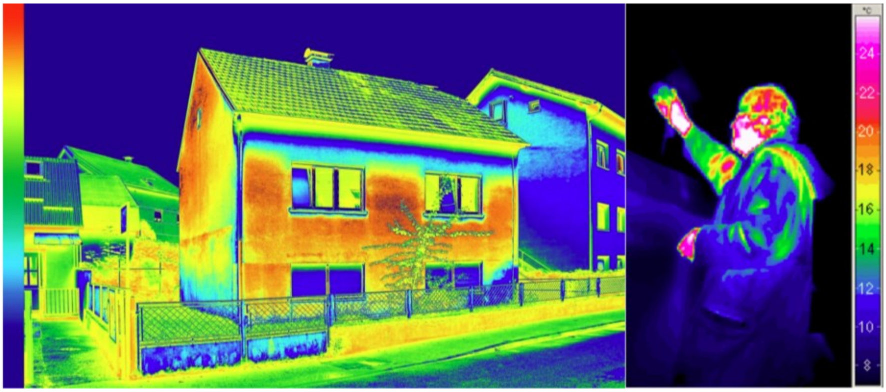

Fig. 11.10 Heat radiation of a house and of a person into the environment. The color change from blue to red and violet indicates higher temperatures in certain zones

A solid, liquid, or gaseous body or medium can *absorb, reflect, or transmit* heat radiation, much like a light radiation.

The respective proportions depend, among other things, on the type of substance, on the surface and on the density of the radiated or radiating system.

The basic equations for the calculation of any radiation are [1]:

$$\dot{Q} = \dot{q}A \quad [W] \qquad \text{with} \tag{11.7}$$

$$\dot{q}_r = \sigma \cdot T^4 \quad \left[\frac{W}{m^2}\right] \qquad \text{and} \tag{11.8}$$

$$\sigma \cong 5{,}67 \cdot 10^{-8} \quad \left[\frac{W}{m^2 \cdot K^4}\right]$$

$\dot{Q}$	$[W]$	energy flux (heat flux, heat flow)
$\dot{q}_r$	$\left[\frac{W}{m^2}\right]$	energy flux density of radiation (heat flux density)
A	$[m^2]$	surface
T	$[K]$	temperature
σ	$\left[\frac{W}{m^2 \cdot K^4}\right]$	Stefan-Bolzmann constant

For two opposite walls which radiate heat at different temperatures to each other this relation receives a practical form:

$$\dot{Q} = \frac{C_S}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)} A_1 \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \tag{11.9}$$

C_S	$\left[\frac{W}{m^2 \cdot K^4}\right]$	radiation constant
ε	$[-]$	emissions coefficient

In general, the behavior of the bodies is similar to light and heat radiation.

Examples of the proportion of absorbed radiation (a) for various substances:

soot	*a = 0,95*
white enamel	*a = 0,91*
black velvet	*a = 0,99*
polished gold surface	*a = 0,02*
polished copper surface	*a = 0,02*

A special case of heat radiation is the flame radiation: In contrast to the radiation of solid bodies, the heat radiation of the gases occurs selectively only at certain wavelengths. The heat absorption takes place analogously on the same wavelengths.

The color of a flame provides information about its temperature and thus about the quality of the heat generated as a result of combustion. Thus, a color change from red over yellow to blue is the result of shortening the emitted wavelength, which indicates the temperature increase.

The temperature distribution during a burning process can be measured optically in a combustion chamber based on the wavelength of the respective radiation, i.e. "from the outside", without disturbing the process sequence[4].

The heat flow emitted into a room from the surface of a body is determined as a function of its temperature to exponent four. The respective equation also contains a physical constant, the value of which was determined by the Austrian scientists Ludwig Boltzmann (1844-1906) and Josef Stefan (1835-1893), as always, phenomenologically.

Heat radiation usually occurs in connection with heat convection and heat conduction, as mentioned at the beginning of this chapter. To simplify the calculations, a "heat transfer coefficient by heat radiation" and a "heat transfer coefficient by heat conduction" are formed. The three coefficients can then simply be added together in a total coefficient.

Thus, a heat flow can be calculated as a product of this overall coefficient, the cross-flow area and the temperature difference.

Example of heat radiation due to fire in a furnace:

A room with an area of 16 m ^{2} has as "central heating", i.e. in the middle of it, a cannon stove in which a fire is burning strongly. The area of the furnace, which emits a temperature of 200°C, is 6 square meters. The model corresponds to a radiated surface that completely surrounds the radiant surface [1].

The heat flow in this case is around 14 kW.

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Part III

The Taming of Fire

12

Pouring oil on the fire

12.1 Climate neutrality: Europe and the world

Some people want to make the fire disappear worldwide in every respect, as quickly as possible, for the sake of climate neutrality. Other people pour fuel on the fire: a part of them have a tremendous hunger for energy, the other part of them want to sell very profitable different energy forms.

Despite all these points of view, the most realistic perspective is to tame the fire: this can be implemented by means of regenerative and thus climate-neutral fuels, but also by recuperation of already consumed energy and last but not least by highly efficient thermal machines.

The firing of hydrocarbons such as petroleum derivatives, natural gas and coal leads to the emission of carbon dioxide. And this in turn leads to global warming as a result of the greenhouse effect (Chapter 5.1).

The balance is clear (Chapter 5.1): the combustion of one kilogram of gasoline results in 3.1 kilograms of carbon dioxide. From the coal, for the same heat, about 7.7 kilograms of carbon dioxide are produced. Natural gas seems to be initially the better choice: Due to the higher content of hydrogen in relation to carbon, the combustion of one kilogram natural gas results in "only" 2.7 kilograms of carbon dioxide and slightly more water than in gasoline or coal combustion.

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_12

The European Union has set itself very ambitious goals accordingly with the Plans of the European Commission: *"The EU wants to become climate-neutral by 2050, with a zero-greenhouse gas emission economy... All parts of society and the economy will play their role in it, from the energy sector and industry to mobility, construction, agriculture and forestry"* [4].

Less than 30 years remain until 2050. The combustion engines are to disappear from all automobiles in the next 10 to 15 years, the drives are to become completely electric, according to the plans of many EU states. If most of the electricity for electric cars did not come from oil, gas and coal, this would certainly be a clean alternative.

Whether the propulsion systems of cargo ships, tankers, cruise ships, passenger aircraft, excavators, tractors, crawlers, agricultural machinery, road construction machines and heavy trucks should also be replaced, there is still an absolute silence.

About the replacement of fire in steel production, casting and molding of machine parts, in the production of cement, in the construction of skyscrapers with high und powerful tower cranes the EU strategy paper reads: *"The EU can lead this course by seeking technical solutions, by empowering citizens ...."* [4].

Nevertheless, there is also a very short and direct way to the target:

The fire will be preserved for thermal machines and plants, but from now on all fossil energy carriers are to be banned completely: *coal, petroleum derivatives and natural gas*.

Although the EU's major objectives for climate-neutral energy use are detailed in many of its documents, they seem to be generally *too detailed*: the appeals of a social, political, psychological or insubstantial but visionary nature do not take into account the real conditions between the energy sources currently used in Europe and in the world. Technical solutions for the rapid replacement of the fossil fuels *coal, oil and natural gas*, which together currently account for almost three-quarters of Europe's primary energy consumption, cannot be derived from such appeals.

And, rather, a European solution is not a solution in the face of the threat of a global climate catastrophe.

In Europe, no more and no less than 13.9% of the world's total primary energy was consumed in 2020. Carbon dioxide emissions in the same year on the old continent amounted to 11.1% of the total emissions on the planet [5].

But the earth's inhabitants are together on a giant ship, which seems to be sinking. Who benefits if eager EU officials want to plug a small hole near the bow, under the luxury cabins? Towards the stern, under the third-class cabins, there are much, much larger holes.

Unless, before Europe's carbon dioxide emissions are completely banned, the promoters of this vision start building an immense, thin and transparent bell around it. Does anyone seriously think that the strong greenhouse provoking currents coming from China, Russia, America or India will slow down in front of Europe's clean air walls? On the contrary, the pressure, temperature and density of a gas or of a gas mixture always go naturally from the high to the lower value, according to the Second Law of Thermodynamics (Chapter 9).

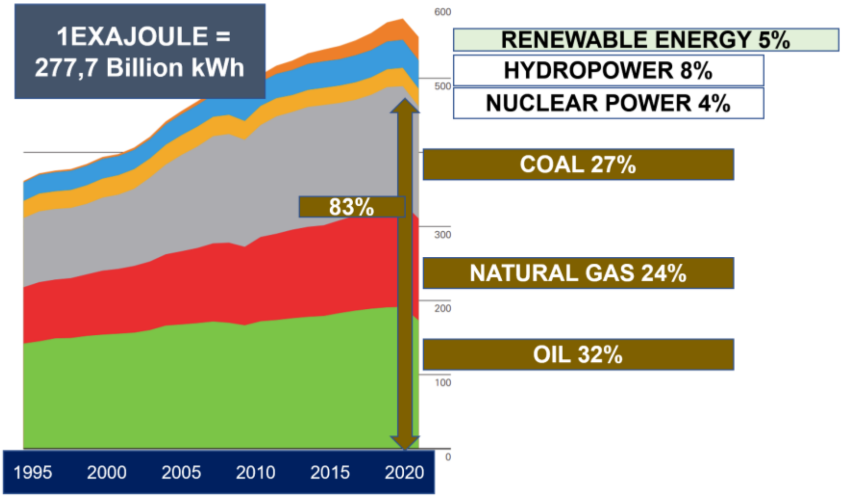

Fig. 12.1 Worldwide actual primary energy consumption (in exajoules) between 1995 and 2020, with the respective shares of the energy sources used (compiled on the basis of the data in [6])

In 2020, primary energy consumption in the world fell by a total of 4.5%, for the first time since 2009 (Fig. 12.1). Oil accounted for the main part of this fall, with 9.7%. With exactly the same percentage, the use of renewable energies has increased. The most important reductions were in North America and Europe (around 8%). In China, on the other hand, primary energy consumption rose by 2.1%.

Despite this encouraging trend, the use of fossil fuels worldwide remains at 83%: coal and natural gas more than half, oil a third! Renewable energies, including wind and photovoltaics, still remain at a modest 5%. And we want to become climate-neutral in Europe by 2050?

In **Europe**, 71.2% of coal, oil and natural gas are currently (2020) used as primary energy sources, but renewable energies achieved, however, 11.5%. Europe consumes (2020), as already shown, 13.9% of the world's primary energy [6].

The prig **Germany** consumes, contrary to the assurances of exemplary use of renewable energies more fossil fuels (75.2%) than the European average (71.2%). Admittedly, this European average is pushed down by nuclear power plants in France and hydropower plants in Norway. Poland, on the other hand, uses 93.2% coal and oil!

In Germany, politicians and many interest groups, including "scientific advisers", assert that more than half of the energy consumed in the Federal Republic is now "green". However, this should not be called "energy" but "electrical energy", which is very rarely said so. In terms of electrical energy, Germany currently (2020) actually uses more than half (51.9%) "green electricity". However, the fact that electrical energy accounts for only 17% of the total energy demand of the Federal Republic of Germany is sobering.

The involvement of fossil fuels in the actual total primary energy consumption in Germany is and remains largely predominant with the participation of currently (2020) 75.2%, as already mentioned (Fig. 12.2). Renewable energy sources (wind, photovoltaics, biomass) account for only 18.2% of the total energy consumed.

Only the shares of lignite and hard coal have fallen slightly since 1990, and much more so since 2018.

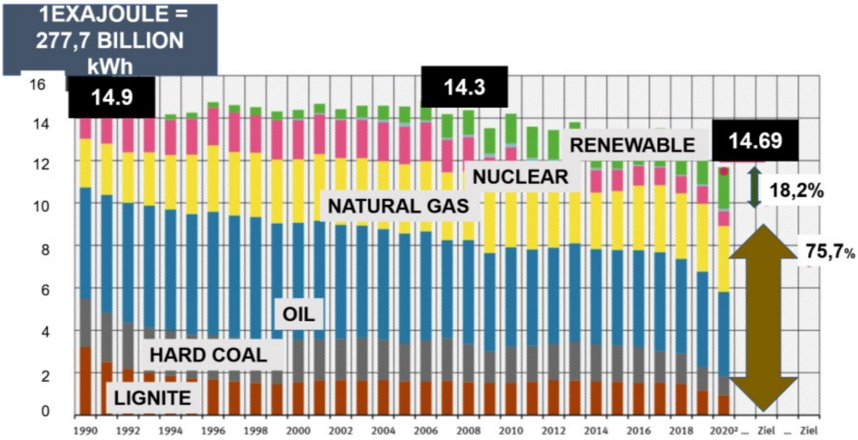

Fig. 12.2 Primary energy consumption in Germany between 1990 and 2020, by energy source (based on data from the Federal Environment Agency, 2020)

In **France**, the share of fossil fuels in the country's total primary energy consumption is only 50%! But at what price? 19% of the energy comes from the 56 French nuclear power plants (out of 130 in the whole of Europe). On the other hand, the share of renewable energy sources in France is with 17%, even lower than in Germany (18.2%).

But there is also, but only at first glance, a prime example of the use of "clean" primary energy: **Norway** uses only 29% fossil fuels and has no nuclear power plants at all. Norwegians are indeed happy people! Nature pours the water directly into the turbines between the numerous fjords. 64% of Norway's energy is produced from hydropower. This also covers 93.5% of the electricity demand, the remaining percentages are made up of wind and heat [7]. This explains Norway's ambitions for all-electric mobility: electric ferries, cars with purely electric propulsion, domestic flights with electric aircraft, the construction sites are electrified!

This is grist to the mill of the advocates of a climate-neutral Europe, not only in the turbines of the Norwegians. However, the reverse of the Norwegian medal should also be seen in this context.

Norway is the second largest oil exporter in Europe (72 million tons in 2019) after Russia (266 million tons) and the ninth largest oil exporter in the world! In terms of natural gas exports, Norway also occupies the 2nd place in Europe, (8.3 billion cubic meters in 2019) after

Russia (19.1 billion cubic meters) and occupies the fourth place worldwide [5]!

The moral of the story is sobering: complete electrification of Norwegian transport on earth, in the air and on the water, for which there is 100% "green" electricity. The dirt is sold to the other states! As if the carbon dioxide emissions of the sold and burned oil and natural gas did not find their way back to Norway via the air!

For the world's users of oil, gas and coal, Europe's plans for climate neutrality are not necessarily an issue.

The **US** uses 82.7% fossil fuels and only 7.3% renewable sources to meet its primary energy needs.

Russia burns mostly natural gas, but also coal and oil, for a total share of 86.4%. Green energy: 0.1%!

Poland, a member of the European Union, uses 93.2% fossil fuels to meet its energy needs, more than half of which is coal!

China is the world champion in terms of primary energy consumption: with 145.46 exajoules (*1 exajoule equals 277.7 billion kWh*) per year, China consumes 1.89 times more energy than the whole of Europe and 1.66 times more energy than the USA. Fossil fuels account for 83.7%. The coal content of 56.5% is striking!

China currently has 1.4 billion inhabitants, India almost as many (1.38 billion inhabitants). However, China currently consumes 4.5 times more primary energy than India.

And **India** also justifiably has a powerful hunger for mobility, industry and home heating. Indians currently use 54.8% coal to cover their energy consumption. The rest of the 90% fossil fuels used are natural gas and crude oil.

Bangladesh, a very poor country, uses almost exclusively fossil fuels.

But Africa is the bigger problem in terms of primary energy: currently 1.26 billion people live in Africa, which is almost as many as in China or India. And the forecasts indicate an increase in the population to 4.28 billion inhabitants by the year 2100 [8].

93% of the primary energy demand on the African continent is currently covered by fossil fuels. Understandably, in view of the large oil exporting countries that belong to Africa, it is 39% oil shares.

The bitter truth is that so far more than 500 million Africans do not have electricity! In the coming years, numerous new coal-fired power plants with a capacity of more than 47 million kilowatts will be built in Africa [8].

Most of them are being built by China, where there are currently (2020) more than 1000 coal-fired power plants, so experience is abundant. But many experts say: [8] *"a rapid global phase-out of coal-fired power is necessary in order to achieve the climate targets"*.

And another quote: *"It is definitely a danger for the climate and for the affected African countries if they do not already rely on climate-friendly development paths. To achieve this, poor countries in Africa would need extensive financial support to enable greater investment in renewable energies*."

And in addition to the Chinese projects in Africa, 1380 coal-fired power plants are planned worldwide [9]!

But where remains the climate-neutral Europe? The current carbon dioxide emissions already speak for themselves: **Europe** accounts for 11.1% of global emissions. **China** emits an impressive percentage of 30.7%, the **USA** 13.8%, **India** 7.1%, **Russia** 4.9%. These countries bring together 56.5% of the global carbon dioxide emissions [5]!

And further? Africa, South America, Central America and Central Asia are future black holes in our Mother Earth universe in terms of energy!

12.2 The profitable oil and gas business

Who in this world wants to give up the sale of oil and natural gas?

There are hundreds of international and national climate protection organizations on the Planet that aim to reduce anthropogenic gas emissions through the combustion of *petroleum products, natural gas* *and coal*. A further warming of the earth's climate above 1.5°C is to be prevented.

The most powerful of these organizations are the following:

The United Nations Framework Convention on Climate Change (**UNFCCC**) as an international environmental agreement with the aim of preventing a dangerous anthropogenic disturbance of the climate system and of slowing down global warming and mitigating its consequences. The UNFCCC Secretariat in Bonn has 450 employees[10].

The United Nations Environment Programme, headquartered in Kenya's capital Nairobi (800 employees) [11].

The **WWF (World Wide Fund For Nature**, until 1986 *World Wildlife Fund*), a foundation under Swiss law based in Gland, Canton Vaud. It was founded in 1961 and is one of the largest international nature and environmental protection organizations. It has 6,200 employees and an annual turnover of almost 700 million euros[12].

In addition, at the world level, but also in almost every state, there are hundreds, if not thousands, of environmental organizations with similar goals.

On the other side, however, are the exporters of oil, natural gas and coal.

Does anyone seriously think that Russia will forego half of the state budget generated by the export of natural gas and oil?

Should Saudi Arabia actually forego 42% of the gross domestic product generated by oil sales?

Or Kuwait on 90% of export revenues? [13], [14].

A look at the list of the world's largest **oil producers** can be very revealing [15]:

The US leads the ranking with 19%, followed by Saudi Arabia (12%) and Russia (11%), then come Canada, China, Iraq, the United Arab Emirates, Brazil, Iran and Kuwait with around 5% each. The US, Saudi Arabia and Russia produce almost half (42%) of the world's oil. And how they participate in the climate conventions can be seen from the national and international press.

The world's largest **oil exporter** is Saudi Arabia with a world market share of 15.4%, followed by Russia with 11.4%, Iraq (8.4%) and Canada (7.8%) [16].

The largest **oil importer** is, as expected, China, with a share of 17.9%, followed by the USA (16.8%) and India (9.3%).

The world's largest **natural gas exporter** is again Russia with a global market share of 19.1% (2019), followed by Qatar and the USA with around 10% each [17].

Regarding the largest **natural gas importer** in the world, we have to be a bit surprised: *This is the Federal Republic of Germany with 10.8% (2019) of all imports by the countries of the world!* [18].

China only comes in second place with 10.1%!

All media in Germany are constantly reporting about the climate change and about renewable energies, which will soon replace all other energy sources almost completely. One can turn the facts, the evaluation criteria and the numbers as it suits him. But if the gas tap is turned off, freezing in winter in our homes and the shutdown of a large part of the industry is guaranteed!

Analysis of the distribution of global production and consumption of *crude oil, natural gas and coal* shows remarkable results.

Daily oil production may show large differences between different regions of the world (Fig. 12.3):

In the Middle East, more than half (53%) of the world's oil is extracted (**produced**), in North America it is 25%, in the old Soviet republics in Asia around 14%.

However, it is interesting in which regions of the world this oil is **consumed**: Asia (this time clearly China, Japan, Korea) "swallows" 63%, although only 14% were produced there. The Middle East, on the other hand, consumes only about 10% of the 53% produced. In America, there is a clear parity between production and consumption, but the balance is given only at first glance: America exports a lot of oil, but also imports a lot, the main thing is that the stock market business remains profitable.

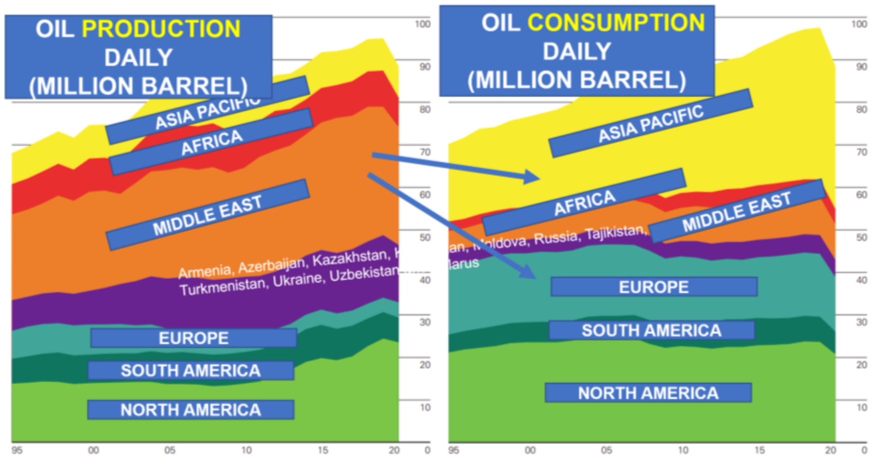

*Fig. 12.3 Petroleum **production** and **consumption** in different regions of the world (according to the [5])*

The largest **natural gas producers** in the world are North America, the Middle East, the former Soviet republics, but also some states in Asia (Fig. 12.4).

The situation is different when it comes to **natural gas consumption**: Asia needs more than it produces, but there are not the same countries (a deeper analysis, however, would go beyond the scope of this book).

The Middle East sells more than it produces, as do the former Soviet republics.

Europe is the big gas consumer in this respect, even if there are differences: Norway exports a lot of natural gas (4th place in the world class), but does not import and consume any natural gas at all!

In North America and South America, production and consumption are largely the same.

As far as **coal production and consumption** are concerned, Asia and the Pacific region account for an overwhelming share of the global distribution at 78% (Fig. 12.5).

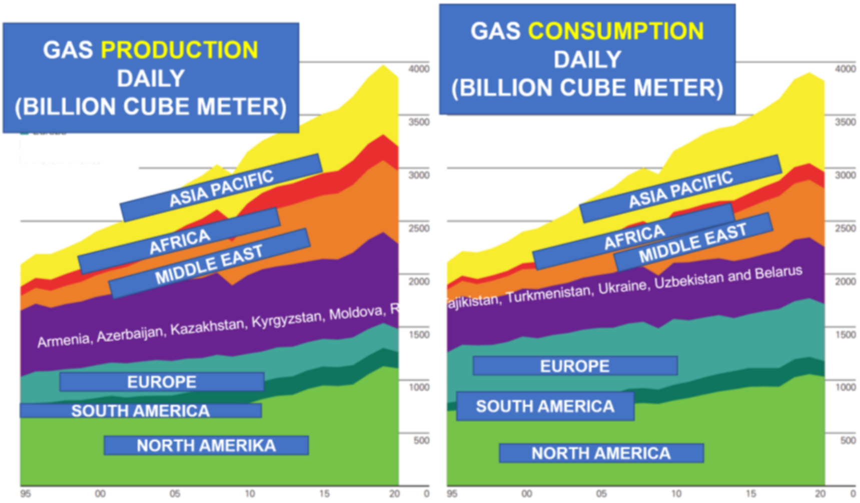

Fig. 12.4 Natural gas ***production*** *and* ***consumption*** *in different regions of the world (according to the template of [5])*

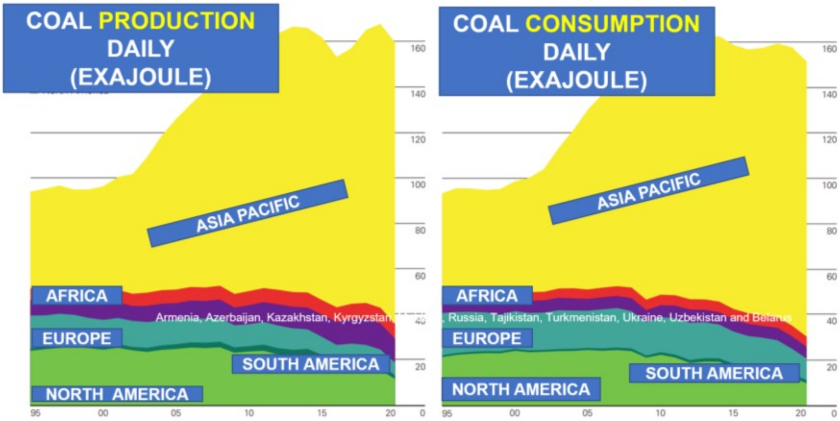

Fig. 12.5 Coal ***production*** *and* ***consumption*** *in different regions of the world (as presented by [5])*

Africa has so far only a very moderate share of coal consumption. But what will happen if China still want to build so many coal-fired power plants in Africa? Do they also send the coal together with the plants?

It is really the last chance in terms of saving the world's climate: but instead of trying to create a model region in the prosperous and technically superior Europe, it would be imperatively to save so many poor countries in Africa, Asia and South America from the oil, gas and coal plague!

13

Fire use with the best possible and climate-friendly effect

13.1 Automobiles with a heart of fire and electric wheels

The neutralization of the climate-damaging effects of fire can be achieved by replacing fossil fuels such as *crude oil, natural gas and coal* with climate-neutral *alcohols, oils and eFuels* (Chapter 4). However, the way there is associated with mass production and infrastructure problems, but above all with the opposition of the current oil, gas and coal vendors (Chapter 12).

As a result, in a first step*, machine configurations* and *thermodynamic processes* should be redesigned with the aim of maximum thermal efficiency and thus minimum fuel consumption and carbon dioxide emissions. These machine configurations and thermodynamic processes (Chapter 10) must be also compatible with the climate-neutral fuels (Chapter 4) to be implemented in the next step.

Fig. 13.1 The internal combustion engines in automobiles from the point of view of their adversaries

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_13

If the campaigns, debates and plans of the present are to be believed, the "Burners” meaning the internal combustion engines will soon be completely and irreversibly banned from the vehicles. It is indeed astonishing how someone with more or less education, but without knowledge of physics, imagines such a "Burner" in his world of thought (Fig. 13.1).

However, the fire in a combustion chamber can be very tame if you offer it the right food and pay a lot of attention to a good “digestion”. It's like with the flowers, the dogs and not only …

To create miracles, the fire needs, like humans, good food and a wholesome digestion.

The fire has its own taste. It's, once again, like with the humans: the food has to taste good to him, the bits have to be distributed one after another in very small portions and above all, with time intervals between them, for taking a breath. Large chunks provoke immediately a stomach rebellion.

A piston engine at 600 revolutions per minute has 0.01 seconds for a whole revolution. Only 5% to 10% of them are available for combustion, which is 0.005 to 0.01 seconds. At 6000 revolutions per minute, only one tenth of this time remains for a complete combustion, which is 0.0005 to 0.001 seconds. At 18,000 revolutions per minute, as is often the case in Formula 1 engines, only a third of this remains, and the engines has still to run at full power.

The problem is neither the load itself, nor the speed: for a certain pairing of load and speed an engine can be always well tuned. However, the fire does not like the often-repeated change of the food portion size for the momentary required load and speed. The engineers do what they can to keep the engine happy in a more or less wide range of load and speed.

But chasing an engine from 3 hp to 1000 hp and from 600 to 18,000 revolutions up and down in a rabid way, then sometimes the fire in it can show black tongues.

It is therefore more effective to burn the fire in a narrow window of load and speed of an internal combustion engine (Chapter 10.2) and to send the obtained work to an electric generator. The produced electricity can be forwarded partly to a propulsion (electric) motor, partly to a storage battery (Fig. 3.9), (Fig. 10.6).

In any case, the propulsion of a vehicle by means of electric motors has a fundamental advantage over that with a thermal machine. In an electric motor, the maximum torque is generated from a standstill, i.e. from zero speed, and remains at this value until about 2000-2300 revolutions per minute. In piston engines, the maximum torque only unfolds in the medium speed range (self-ignited engines) or at higher speeds (spark-ignition engines), which is due to the required air flow for the burning process within the combustion chamber.

The propulsion by means of an electric motor therefore appears to be particularly favorable for city driving because of the rapid start-up and the practically gearshift-free operation.

A vehicle can be driven by a single electric motor, by two electric motors (one on the front axle, one on the rear axle) or by 4 electric motors (two each on the front and rear axle, close to the wheel). However, the wheel hub motors are much more advantageous for driving dynamics, driving stability and degrees of freedom of wheel movement (Fig. 13.2).

Fig. 13.2 Wheel hub motors for vehicle drive: Mitsubishi (left), Michelin (middle), Honda (right) (Sources: Mitsubishi, Michelin, Honda)

A wheel hub motor of this version usually achieves an output of 20 kW and a torque of 200 Newton meters [3]. If enough electrical energy is available on board, each wheel can be equipped with such a motor. The classic front and rear drive axles are no longer required in such a case. As a result, the degrees of freedom of the kinematics of each wheel increase. In addition, these degrees of freedom on each wheel are in principle <u>independent</u> of those of the other wheels.

The advantages in terms of kinematics and dynamics of the vehicle are remarkable, which can be proven by a few examples:

- According to driving situation, the propulsion can be switched between all-wheel, front-wheel or rear-wheel drive solely by controlling circuits. Functions such as ESP, ASR or ABS are more effective and can be implemented with a higher quality.
- Parking and turning manoeuvres are extremely facilitated, from entering a parking space from the side to turning around an axis with a narrow circle. Especially for urban use, such functions are indispensable in view of the rapidly increasing traffic density.
- The driving stability in curves can be significantly increased by the pairwise steering of the front and rear wheels.

In newest development projects, hub motor wheels are considered as intelligent driver assistance systems [3]. The mechatronic approach and the trend towards autonomous driving find their origins in robotics. As with robots, in automobiles, a position is defined by the 6 degrees of freedom of a coordinate system – these are the movements in the longitudinal, transverse and vertical axes as well as the rotation around each of these axes. Data and information are exchanged in the driver assistance system as in the robot via bus systems, preferably with real-time capability.

And now back to the thermal machine, which can work as a power generator on board of a vehicle. There are several types of machines to choose from, with different thermodynamic cycles. (Chapter 10.2):

1. Piston engine with external combustion, according to the Stirling cycle.
2. Piston engine with internal combustion, according to the spark-ignition (gasoline), compression-ignition (diesel) or Seiliger cycle.
3. Gas turbine with internal combustion, according to the Joule cycle.
4. Steam turbine with external combustion, according to the Ackeret-Keller cycle.

1. Stirling engines (Chapter 10.2) would be tempting for such a task because of the theoretically very high thermal efficiency. However, due to external combustion, they can hardly reach the maximum temperature which could be achieved in a gasoline or diesel engine with internal combustion. On the other hand, heat recuperation is only possible with large heat exchanges, which is unfavorable for mobile use.

2. Modern gasoline or diesel engines (Chapter 3.3), (Fig. 3.6), (Chapter 10.2) are suitable, but in general mechanically too complex for such operation mode: four valves per cylinder or turbocharger are too sophisticated. Simple, lightweight, small and inexpensive two-stroke engines, Wankel engines with rotating pistons and compact gas turbines, all working in a fixed load/speed, can accomplish the same task.

3. The gas turbines with internal combustion according to the Joule cycle (Chapter 3.3), (Fig. 3.9), (Chapter 10.2), (Fig. 10.6) have a lower thermal efficiency compared to other engine versions, but they can allow a high air-mass flow, thus of fuel, due to the usual high revolution speed, which makes them extremely light and compact. A great advantage of a gas turbine consists of its open combustion chamber, with constant air and fuel flow. This makes it possible to use kerosene just as well as diesel fuel, coconut oil or ethanol and methanol.

4. The steam turbines with external combustion and heat recuperation are highly recommended for power plants, but are not suitable for mobile applications due to the price, but also to their dimensions.

13.2 Combustion engines on water, on earth and in the air

It may be that the combustion engines or the "burners", above all, the discredited diesel engines will be banned from the road traffic. But on the seas and oceans of the world, the real conditions force a different course of action.

What would a powerful ship be without a diesel engine? Marine diesel engines are available in almost all classes. The largest and most powerful marine engines are in general slow-running two-stroke engines [3]. Four-stroke engines are built in large and medium power classes as medium-speed engines, small marine diesel engines are often high-speed machines.

Marine diesel engines of all kinds can in principle be operated with many different fuels.

In tankers and container ships, gigantic diesel engines are used, which turn very slowly (*60 to 250 revolutions per minute*). They drive the propeller directly via a rigid axis. And, if the combustion has so much time, one can also marvel at the effect of fire: Such engines achieve efficiencies of over 50%, which is not yet the case in high-speed automotive engines.

The largest marine diesel engines are designed, as already mentioned, almost as two-stroke engines *(at first glance like the Trabant or Vespa engines, which are not compression-ignited, but with spark-ignited, using gasoline. They have no direct injection of fuel, but carburetors).*

A look into the cylinder of such a large two-stroke engine would be worthwhile: one-meter piston diameter, 2.5 meters piston stroke. The Wärtsilä-Sulzer 14RTflex96-C [19] engine has 14 cylinders and delivers 109,000 hp (Fig. 13.3). An electric motor or motor package with this power might be conceivable as a replacement of the big two-stroke machine, but the necessary battery volumes and weights would fill the ship completely (*instead of the containers to be transported*) if it did not sink during battery loading on board!

Fig. 13.3 The Wärtsilä-Sulzer 14RTflex96-C engine with 14 cylinders and 109,000 hp (Source: Wärtsilä)

High-speed and medium-speed engines are used in ships for rather moderate performance. In such a case, it is necessary to reduce the engine speed to propeller speed. Some of the transmissions used are equipped with switchable clutches and power drives.

However, most ships have been sailing for a long time like the automobiles of the future described above: They are powered by electric motors that draw their electricity from diesel-engine-powered generators: 80% of ocean-going ships are equipped with such "diesel-electric" drives [20].

The next steps towards climate-neutral "combustion engines" are:

- the use of renewable fuels (Chapter 4) und
- the modification of the combustion technique within the diesel process (Fig. 4.3).

Large-scale diesel engines using the four-stroke process, with 100% methanol direct injection, have been developed and put into series production for use in Wärtsilä ships. B&W/MAN has also built diesel engines with methanol direct injection for ship use. In this case, however, these are two-stroke engines, which have advantages over four-stroke engines in terms of weight and dimensions for the comparable enormous power [3].

Both the four-stroke engines from Wärtsilä as well as the two-stroke engines from B&W/MAN use a fundamentally different combustion technique in comparison with the classic diesel compression ignition: By means of pilot direct injection of a slight amount of diesel fuel, small glowing balls are created in the combustion chamber, from which the main amount of methanol injected is quickly ignited and burned (Chapter 4), (Fig. 4.2). This significantly reduces both fuel consumption and nitrogen oxide emissions.

The Wärtsilä four-stroke methanol diesel engines with pilot injection are used on the ferry Stena Germanica (2015), while the B&W/MAN two-stroke methanol diesel engines with pilot injection with their 10,320 kW equip the tanker Lindager. The methanol for the "Stena Germanica" is produced on the basis of carbon dioxide (Chapter 4.3), which was intercepted from blast furnace gases from steel production, similar to the process in (Fig. 4.2) by SSAB in Luleå [21].

The Danish container shipping company Moeller-Maersk has also ordered eight large container ships to run on "green" methanol from 2024. They each have a capacity of around 16,000 standard containers (TEU) and are expected to reduce the shipping company's carbon dioxide emissions by one million tons per year (from 33 million tons in 2020). Methanol also releases fewer particles and other pollutants than the combustion of diesel fuel or heavy fuel oil. The new ships will be built by Hyundai Heavy Industries in cooperation with the marine engine manufacturer MAN.

Identical or similar engines are also used for stationary operation in power plants on islands and in remote places on the mainland: They also serve as emergency power generators in hospitals, as well as in large banks, data centers, but also in nuclear power plants (Fig. 13.4).

Not only the "green" methanol, but also the hydrogen is currently finding its way into internal combustion engines as a fuel for the future.

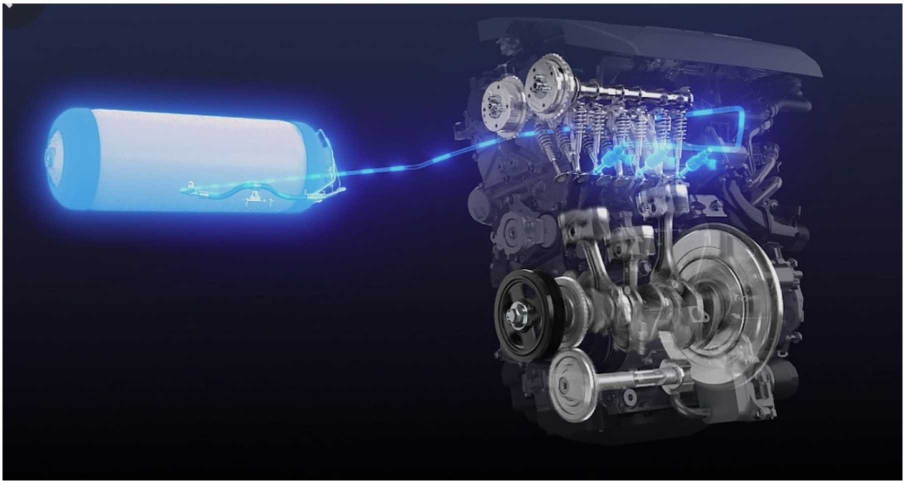

Fig. 13.4 Diesel-like piston engine with hydrogen as fuel injected from a tank under a pressure of 700 bar directly into the combustion chamber, at 20-25 bar (source: Automobilproduction, 4 June 2021)

Since August 2021, the major German engine company Deutz has been building a six-cylinder engine (TCG 7.8 H2) [22] with hydrogen direct injection, based on a previously produced series diesel engine.

The new hydrogen engine, which has an output of 200 kW, is designed for use in agricultural machinery, off-road vehicles and construction machinery (Fig. 13.5).

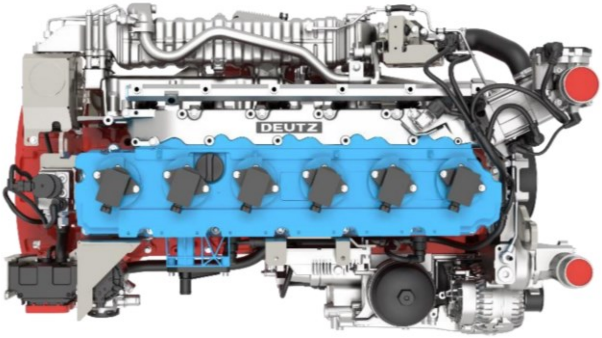

Fig. 13.5 The Deutz six-cylinder piston engine with hydrogen direct injection (Source: Deutz AG)

For freight transport on roads, by truck, a hydrogen piston engine of the other German large engine company, MAN, was developed at the same time [23]. It is also based on a six-cylinder diesel engine in production and has an output of 368 kW and a maximum torque of 2300 Newton meters (Fig. 13.6).

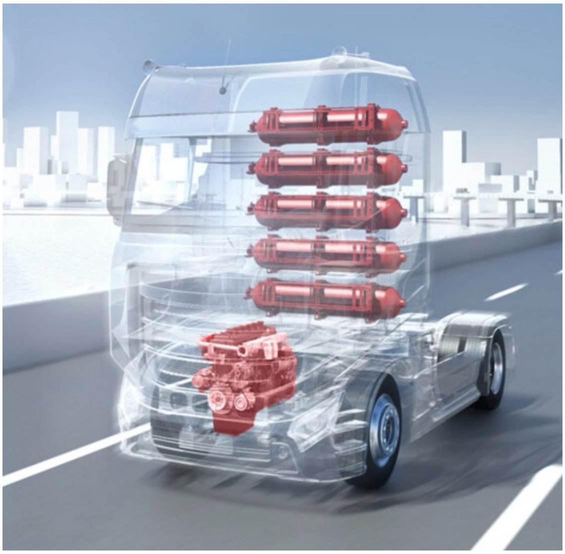

Fig. 13.6 Truck with hydrogen engine (Source: FEV)

The compression ratio has been reduced compared to the diesel basic engine in view of the combustion technique for hydrogen. The injection pressure has been significantly reduced as well.

The hydrogen tanks are under a pressure of 700 bar. The engine achieves an efficiency of 43%. As a result of hydrogen combustion with aspirated air, neither particles nor carbon dioxide are produced. The only problem would theoretically be nitrogen oxide emissions, provoked by the reaction of nitrogen in the combustion air with the remaining oxygen. However, due to the specific combustion technique and to the catalytic post-treatment, such emissions are pushed far below the permissible limits [24], [25].

Air traffic can also become climate-neutral in the foreseeable future when powered by “Burners" : Airbus, Rolls-Royce, Neste and the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) are currently investigating the behavior of climate-neutral fuel in a turbofan engine which equips the Airbus A 350 (Fig. 13.7) [26].

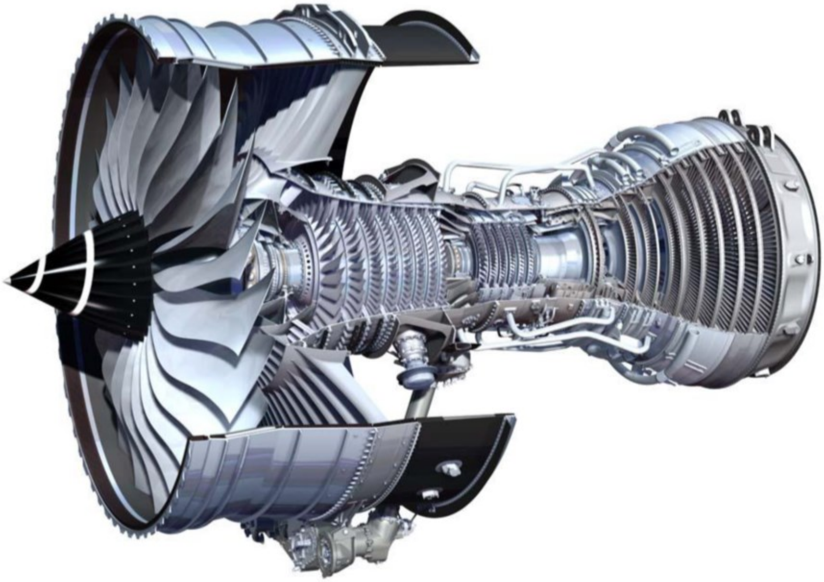

Fig. 13.7 Turbo-fan engine Rolls-Royce Trent XWB with climate-neutral fuel for the Airbus A 350 (Source: Rolls-Royce)

The most developed within the group of sustainable fuels SAF (Sustainable Aviation Fuels) is HEFA (Hydroprocessed Esters and Fatty Acids), which consists, among other components, of *waste fats and waste from the food industry*. In addition, biokerosene from solid raw materials, such as cereals *or algae*, has recently been implemented for use in aircraft engines. The SAF also include so-called power-to-liquid fuels (synfuel), which are produced by the synthesis of hydrogen and carbon dioxide (Chapter 4), (Fig. 4.2). The great advantage of SAF fuels is that no changes to the existing aircraft or to the infrastructure at airports are necessary.

In another current project, ECLIF3 (Emission and Climate Impact of Alternative Fuels), Airbus, Rolls-Royce, SAF manufacturer Neste and DLR want to investigate how pure HEFA fuel behaves in terms of performance and emissions. Currently, SAF is approved for mixtures with kerosene of up to 50 percent

13.3 Fire for electricity and heat

Electrical energy and useful heat are currently generated together in combined heat and power plants, and increasingly in smaller, modular combined heat and power plants. *Gasoline and diesel engines* (Fig. 10.1), (Fig. 10.4)*, gas and steam turbines* (Fig. 3.3), (Fig. 10.5) and *Stirling engines* (Fig. 10.2) are utilized as heat engines for converting fuel energy into mechanical work for power generators *and* into heat for warming. Mixtures of natural gas and biogas are very often used as fuels.

The advantage of *combined heat and power* over separate plants for the production of heat and of electrical energy lies in the more efficient use of fuel energy.

In power plants for the sole generation of electrical energy by means of a heat engine, which is often a classic piston engine, about 30% of the heat supplied for engine cooling and a further 30% by the exhaust gas heat are generally released without utilization into the environment.

In power plants that generate heat in addition to electricity, these two components are used for heating purposes or for other heat applications, which increases the total thermal efficiency of such an internal combustion engine to 80% - 90% (Fig. 13.8).

This makes the combustion engine equal to an electric motor in terms of efficiency.

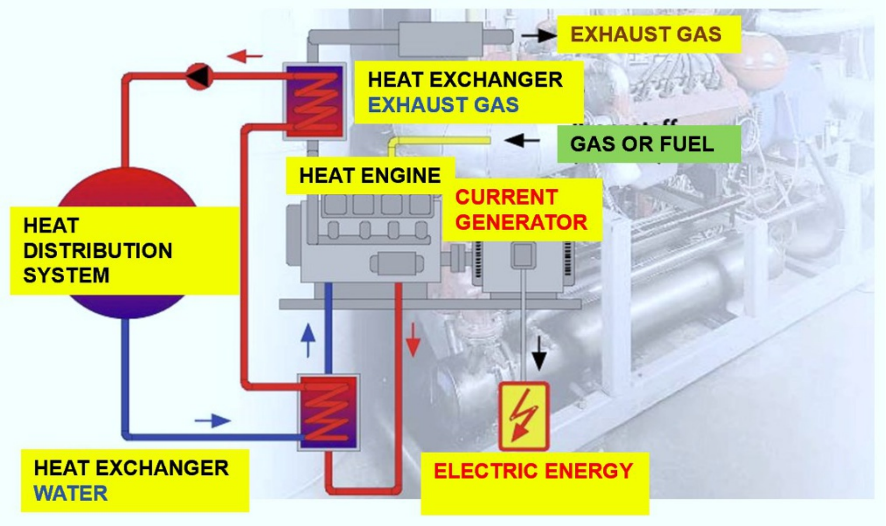

Fig. 13.8 Schematic of a combined heat and power plant with recovery of engine cooling water heat and engine exhaust heat

Example

In two new plants of this type, which were put into operation in 2020 in a German town with around 250,000 inhabitants, groups of five and seven large gas engines are used to generate 150 megawatts of electrical power and 130 megawatts of thermal power. For the heat supply of the respective town, three additional boilers are fired with natural gas/biogas and provide a total output of 100 megawatts. The combination of engine power plants and boilers with the same fuel, natural gas/biogas, is currently one of the most modern forms of supply of electrical energy and heat, thus achieving a reduction in carbon dioxide emissions of up to 40% compared to traditional coal-fired power plants.

A further alternative regarding the generation of *electrical energy* and *heat* by the intelligent combination of thermodynamic cycles (Chapter 10), of different types of machines (Chapter 3), working fluids (Chapter 8) and fuels (Chapter 4), forms the group of **Combined Cycle Power Plants**.

At first glance, such combinations seems to be rather confusing. Depending on the kind of presentation, however, they can also be made to appear very clear (Fig. 13.9):

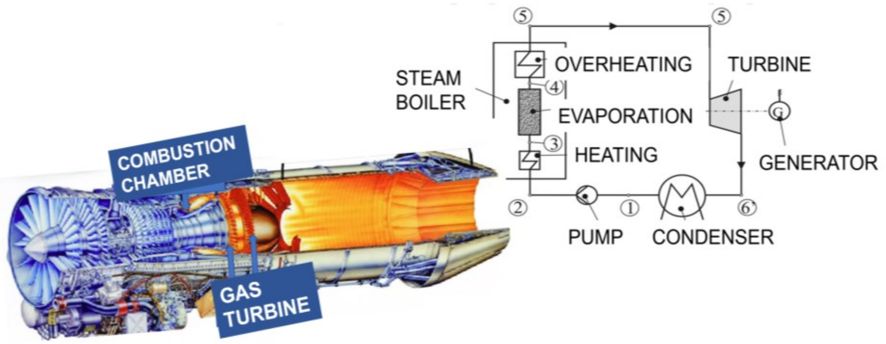

Fig. 13.9 Schematic of a combined cycle power plant, named also Combined Cycle Gas Turbine (CCGT) resulting from the integration of a gas turbine (Fig. 3.7), (Fig. 10.7) in a power plant with a steam turbine (Fig. 3.3).

Let us integrate a gas turbine (Fig. 3.7), (Fig. 10.7) into a power plant with a steam turbine (Fig. 3.3).

The gas turbine works using a direct effect of fire (Chapter 3.3): The burnt air-fuel mixture acts in the turbine as a hot gas within a joule cycle (Chapter 10). As currently used in aircraft construction, instead of kerosene, a HEFA (Hydroprocessed Esters and Fatty Acids) made of *used fats and waste from the food industry* can be fired.

In a classical power plant, with an indirect effect of fire (Chapter 3.2) a steam turbine operates in the closed circuit of the working medium water within a cycle consisting of the same elementary process sequences (Chapter 8.2) as the Joule cycle in a flow machine (gas turbine).

The combination of these two systems has the following characteristics:

- Both the steam turbine and the gas turbine drive a separate power generator.
- The hot exhaust gas flow after the gas turbine is fed into the heat exchanger (boiler) of the steam turbine's water circuit.

Exactly at the coupling point, this configuration shows its effect: under grandma's hot water boiler in the bathroom there was a wood or coal fire. In the coal-fired power plant, the boiler is heated similarly, in nuclear power plants it is similar, the heating takes over in this case a separate liquid power run, in which the nuclear fission leads to liquid heating.

All these three forms of heating have a common particularity: the heat transfer from the hot medium to the steam circuit consists more of heat conduction (Chapter 11.2) than of convection (Chapter 11.3). In comparison, the accelerated heat jet from the gas turbine of the turbomachinery has a considerable convection component. This makes the heat transfer from the hot exhaust gas to the water vapor very efficient.

The exhaust gas temperature after the combustion chamber of such a turbomachinery is generally 1600°C, the temperature of the exhaust gas jet after the turbine is 550°C to 650°C. By several circuits of the steam during compression and rather during the expansion (*intermediate overheating by returning secondary circuits into the boiler*), the entire process in the steam circuit is gradually "pushed" towards an Ackeret-Keller (Ericsson) cycle (Chapter 10.2). Such a thermodynamic cycle theoretically has the same, unsurpassable thermal efficiency of a Carnot process or of a Stirling process *(87% at a maximum temperature of 1900°C).*

Modern combined cycle power plants currently achieve efficiencies of 63% [27], [28] with outputs in the range of 1,700 megawatts.

For comparison:

- A medium nuclear power plant achieves outputs in the range of 1,600 megawatts, with an efficiency (*based on the energy balance well-to-wheel*) of 35%.

- A coal-fired power plant unit achieves outputs of 100 to 1,000 megawatts with average efficiencies of 40%.
- an offshore wind turbine achieves an output of up to 5 megawatts, an onshore wind turbine up to 4 megawatts.

Although combined cycle power plants with climate-neutral fuel could be replaced by a number of wind turbines, more than 400 of them would be needed to replace a single power plant. And they primarily only supply electricity, but no heat.

14

Second-hand Fire

14.1 Electricity and heat from waste firing

Combustion engines and power plants of all kinds can also be fed with second-hand fire. The combustion of residual waste (Fig. 14.1) certainly also produces carbon dioxide. However, in most cases, waste incineration pollutes the atmosphere with carbon dioxide, in addition to the power plants where electricity and heat are generated:

Fig. 14.1 Garbage fire in a residual waste treatment plant

There are currently more than 2200 waste incineration plants worldwide, in which around 280 million tons of waste are burned. By 2025, an increase to 2750 plants for 430 million tons of waste is expected [29].

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_14

In Germany, 66 waste incineration plants with a capacity of around 21 million tons are currently in operation [30].

Waste generally refers to the proportions of garbage that can burn with oxygen from the air at ambient pressure. These include household garbage and municipal garbage, most of which contain organic hydrocarbons. The calorific value of such waste is a quarter of the usual values for gasoline and diesel fuel [1]. From one kilogram of humid waste, 0.36 kilowatt hours of electrical energy can be obtained, taking into account the process stages and the associated efficiencies.

In a waste incineration plant, after waste drying at over 100 °C, degassing is carried out at 250-900 °C and then follows the burning under oxygen lack at 800-1150 °C. The resulting gases are carbon monoxide, unburned hydrocarbons and a low nitrogen oxide amount [2]. In a further stage of the burning process, air is supplied again, whereby the intermediates are completely burned into carbon dioxide and water. This two-stage combustion process is similar to that used in earlier diesel engines with pre-chambers and vortex chambers [3] This burning technique in two stages ultimately serves to a complete combustion with minimum amounts of carbon monoxide and nitrogen oxides.

The resulting flue gas releases the heat to the heating surfaces of the steam boiler, which provides hot water.

During the waste burning process, it is not known which substances are contained in it, participating to the combustion process in certain instants of time. Critical are, for example*, PVC, batteries, electronic components and paints*, which can produce hydrochloric acid hydrofluoric acid as well as mercury and dusts containing heavy metals. For this reason, exhaust gas purification is particularly important. This in turn helps to obtain clean carbon dioxide, which can be used for the production of methanol in a further synthesis with hydrogen (Chapter 4.3), (Fig. 4.2).

Every European “produces” annually 475 kilograms of waste on average. The Germans are a bit more economical with the garbage, they produce "only" 455 kilograms per year. But that's at least 1.3 kilograms of garbage every day!

The usual way of the garbage leads, after separation, directly to the incineration plants.

But there is also a better way: In two modules of the Combined Heat and Power Plant Munich North, 650,000 tons of residual waste are incinerated annually. By way of comparison, 800,000 tons of hard coal are fired in another module of the same Combined Heat and Power Plant. By burning these two energy donors, 900 megawatts of heat and 411 megawatts of electrical power are generated [31].

The annual carbon dioxide emissions of the entire plant amount to around 3 million tons per year (2015). By way of comparison, Thyssen Krupp's Duisburg steelworks produce 8 million tons of carbon dioxide annually.

A true model of Combined Heat and Power Plant with waste burning is located in Bolzano, Italy (Fig. 14.2). The respective region of South Tyrol has one of the strictest ecological environmental laws in Europe, from collection to recovery of all types of waste: 52% of the region's waste is recycled, 44% is burned, only 4% is stored. In the mentioned plant, 130,000 tons of waste are burned annually [32].

The facility generates 59 megawatts of heat and 15 megawatts of electrical energy. The concentrations of all pollutants emitted remain far below the particularly strict European standards: dioxin emissions are only 1% of the standard, nitrogen oxide emissions remain only 15% of the standard, the particles 8% of the standard. The exhaust gas flowing through the chimney consists practically only of carbon dioxide and water vapor.

A second-hand fire made of garbage not only helps to relieve overcrowded landfills. It also generates electricity and heat, with a considerable share, in addition to the central supply networks.

„Second-hand-fire” Combined Heat and Power plants (CHP) in the landfill vicinity of each locality could establish a solid decentralized electricity and heat supply system. As a result, long transport routes for electricity and heat, which are associated with significant energy losses, could be avoided. Instead of gigantic and cost-intensive combined heat and power plants, which rarely fit into the landscape, many smaller waste burning plants with electricity and heat production appear to be more efficient in every respect.

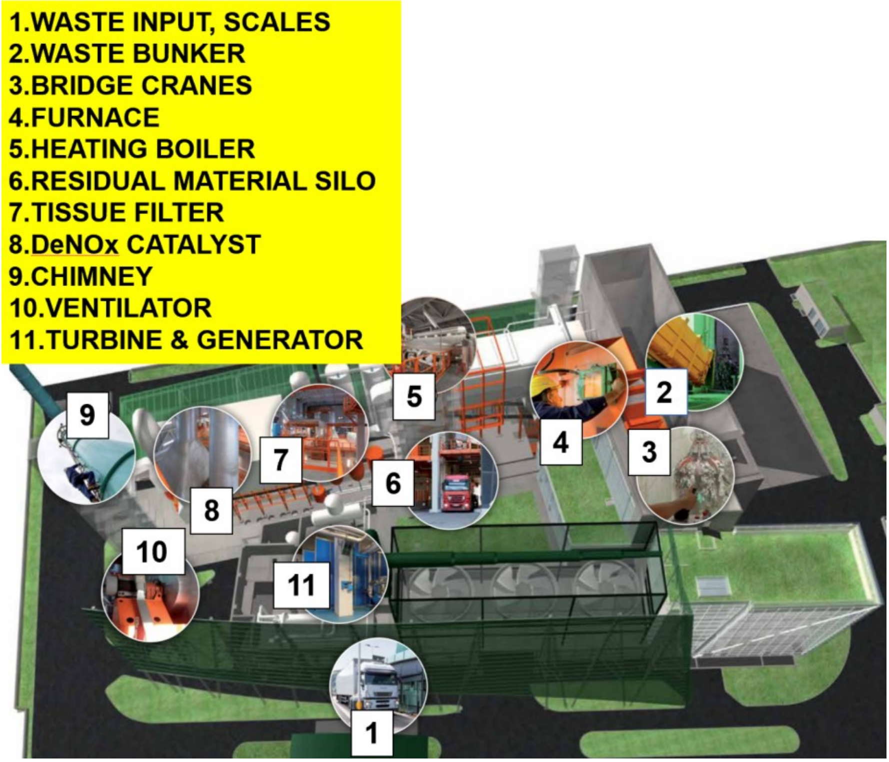

Fig. 14.2 Combined Heat and Power Plant with waste burning in Bolzano/Italy – functional schematic (Source: ECO Center AG, Bolzano)

14.2 Slurry, manure and plant residues as a basis for second-hand fire

Biogas is produced by fermentation of slurry, manure, food residues, lawn clippings and plant residues.

The biogas contains 50% to 75% methane. Methane has about the same calorific value as gasoline and diesel fuel [1]. It is therefore also used as a fuel in heating systems, combined heat and power plants and heat engines of all kinds.

For example, *pig slurry* has a biogas yield of 60 m^3/ton with 60% methane content, *chicken manure* 80 m^3/ton with 52% methane content, *biowaste* 100 m^3/ton with 61% methane content [33].

Biogas is an explosive product of the decomposition of organic components in the biomass by microorganisms, by lack of oxygen. During this process*, the carbohydrates, proteins and fats contained* are mainly converted into *methane and carbon dioxide*.

Due to the same properties, the methane in the biogas can be mixed with fossil natural gas in any proportion. Both can be used separately or in variable mixtures in combustion plants and in internal combustion engines for stationary or mobile use as fuel.

The use of biogas in internal combustion engines which act as generators drives for production of electrical energy within a biogas plant (Fig. 14.3), is particularly advantageous. In Germany, there are 9500 such decentralized plants (2019) [34], in other countries, this type of use of biogas is increasing.

Example:

In a small, rural biogas plant in Eastern Europe, so much biogas is extracted daily from 55 tons of cow manure from a single neighboring farm and burned in one internal combustion engine that the coupled generator can supply 370 kWh of electrical energy. This energy would be enough to fully charge the 32 kWh batteries of 11 VW eUp [3]. However, this biogas could also be used to fire internal combustion engines in vehicles.

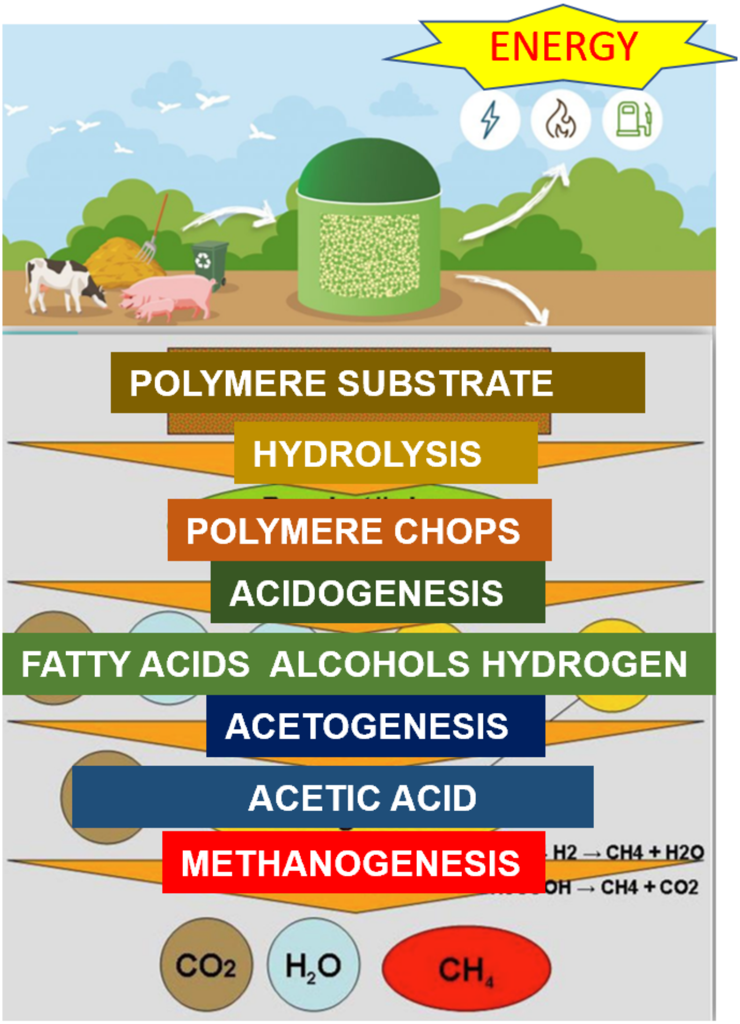

Fig. 14.3 Biogas plant with coupled biogas cogeneration plant for electricity and heat supply and process sequences in the formation of methane

Automotive drives with biogas-powered internal combustion engines have particularly great potential in terms of globally reducing carbon dioxide emissions.

Due to the similar values of air demand and calorific value of methane and gasoline, a conversion of vehicles with gasoline engines to biogas operation (methane) is largely unproblematic [3]. Such a change is particularly favored by the significantly higher octane number of methane compared to gasoline: In engines which only work with methane, the compression ratio can be therefore increased, causing a noticeable improvement of the thermal efficiency and thus a proportional decrease of the fuel consumption.

In an automobile, however, the gas must be stored on board. With the very low biogas/natural gas density compared to gasoline or diesel fuel, a conflict between tank volume and vehicle operation range appears. The gas must therefore have a higher density. For biogas/natural gas, the usual pressure in a tank on board a vehicle is 200 bar (Fig. 14.4) [35] .

Such a compressed methane is commonly referred to as CNG (Compressed Natural Gas). The gas density of methane at 200 bar is 0.131 kg/liter (*water has, as a comparison, a density of 1 kg per liter under ambient conditions).* At 0.75 kg/liter, liquid petrol has almost six times the density of compressed methane (CNG), with about the same calorific value, expressed in kilojoule/kilogram. This significantly impairs the operation range of the vehicle [35].

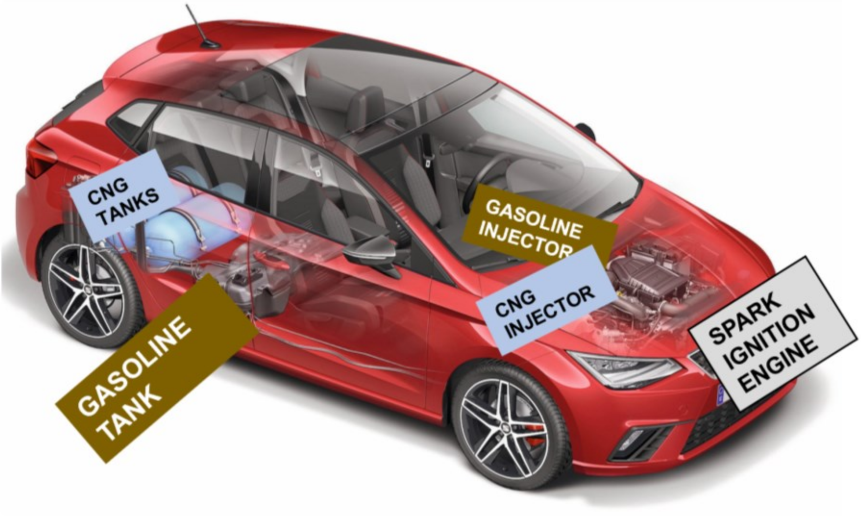

Fig. 14.4 Automobile with spark ignition engine for bivalent operation with methane gas (CNG at 200 bar) and gasoline, with separate tanks (Source: SEAT)

An alternative to increasing the pressure for higher methane density is the temperature reduction. At minus 161-164 °C and ambient pressure, the methane is liquid. Methane, known in this state as LNG (Liquefied Natural Gas), reaches three times the density of CNG. However, cryogenic storage technology is technically more complex and costlier. Therefore, this variant is primarily used on large ships, especially in LNG-transporting tankers. There are currently (2020) over 320 LNG-powered ships and over 500 new ship orders [2].

On the road, LNG is not used for automobiles due to the cost-intensive storage, but only for large commercial vehicles. Two representative examples are the trucks of Scania with 302 kW spark plug engines and IVECO with 339 kW spark plug engines. Volvo has developed diesel engines with LNG injection, in which the ignition takes place by means of a pilot injection of a small amount of diesel fuel [3]. The use of bio-LNG in vehicles with gasoline and diesel engines therefore appears as very promising.

And if bio-LNG can be used in internal combustion engines, why not bio-methanol as well?

Methanol, and also bio-methanol, has the main advantage of being liquid at ambient pressure and temperature, at the same density as gasoline. Bio-methanol can be produced from biogas by its synthesis with hydrogen. The energy for electrolytic hydrogen production can be generated by the biogas-powered combined heat and power plant at the biogas plant or by the wind/solar power plants installed there.

At this point, it is necessary to weigh up what brings more advantages in terms of technical effort and costs: The production of frozen LNG and its storage and injection via thermally insulated plants, or the production of bio-methanol from biogas and hydrogen, whereby liquid methanol can be stored and injected just as effortlessly as gasoline. Future pilot projects will show this.

14.3 Second-hand heat from primary fire

A primary fire in the combustion chamber of an internal combustion engine creates heat that is to be converted into work. According to the

First Law of Thermodynamics (Chapter 7.1) it is not possible to generate work that could be greater than the heat invested. That would be a perpetual motion machine of the 1st kind.

But could the engine generate more heat than the heat supplied to it? That would be a particularly efficient solution for all heating and hot water systems in single-family homes, factory halls and office buildings in which or for which coal and gas are now burned!

Such an engine would therefore have a unique position among all machines in the world:

An ideal internal combustion engine is designed to eat biogas from waste to generate heat that is converted into a slightly less work, whereby four times more heat than the original one arises!

Would that be a fourth-degree perpetual motion machine? By no means!

We just need to clearly distinguish an energy conversion (from heat to work) from an energy transport (heat by means of work):

Energy conversion: A heat engine, such as a diesel engine, receives heat from the combustion of a fuel with oxygen from the air and converts it into 40-47% work. The rest of the heat is normally released into the environment by engine cooling (25-28%) and via the burned and expelled gases (25-30%) at high temperatures of 500-700°C. A small percentage of the supplied energy is also lost as friction in the moving engine parts.

Energy transport: Heat can be absorbed by a lower temperature system and transported and transferred to a higher temperature system if mechanical work is done for this transport. The work corresponds to the difference between the released and the supplied heat [1].

The heat of wastewater from residential and industrial buildings or from cooling water of internal combustion engines and other plants or processes can already be transferred from a temperature of 10 ° C -20 ° C to a working medium in a closed-circuit using heat exchangers. Due to its following compression at temperatures of 70 ° C - 80 °C the working medium can be then transferred to a coupled heating system via heat exchangers. Appropriate work is required only for the compression of the working medium (Fig. 14.5).

Example:

If a wastewater flow passes through a pipe with a diameter of one meter, being wrapped in a spiral heat exchanger pipe over a length of 70 meters and thus releasing only 4 °C, a heat flow of 33 kilowatts is already generated. This heat flow is transferred to the working medium in the heat exchanger tube.

The working medium in damp form can then be brought to a higher pressure by means of a compressor. Therefore, its temperature increases, for example up to 70 °C.

In this state, the working medium transfers a corresponding heat flow to the water in a heating circuit via a heat exchanger (radiator). After the heat exchange, the partially condensed working medium is brought to the original pressure when traversing an expansion valve or choke, which lowers not only the pressure but also its temperature, far below that of the wastewater flow at the entrance to the spiral heat exchanger, from where the cycle begins again.

The working medium is chosen so that it can condense in the heat exchanger on the wastewater side and vaporize in the heat exchanger (radiator) on the heating circuit side. As a result, an intensive heat exchange is ensured in both heat exchangers.

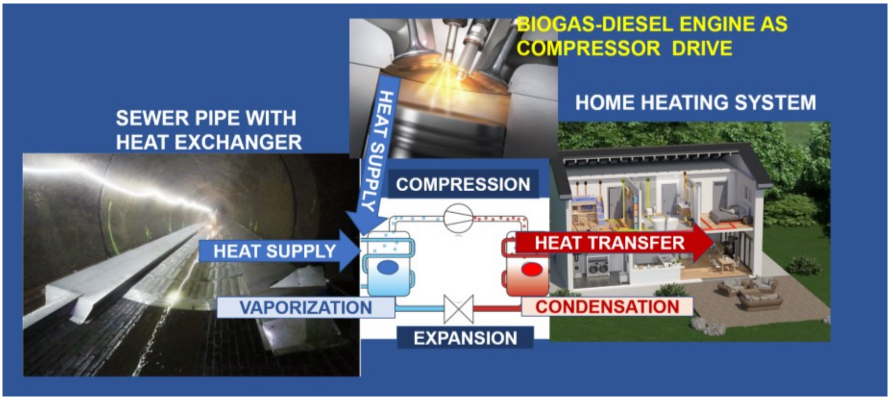

Fig. 14.5 Functional schemata of a heat pump using wastewater as the main heat source as well as the cooling water and exhaust gas heat of the driving heat engine as auxiliary heat sources

The transport and compression of the working medium, as mentioned, are carried out by a compressor. The compression work can be carried out either by an electric motor or by a heat engine. An electric motor has an efficiency of 90 – 95%, but the electrical energy is generally supplied to it by a power plant. Depending on the energy source used – coal, natural gas, crude oil or nuclear energy – this has an efficiency of 25% to 50%. As a result, the overall efficiency when using a compressor with an electric motor remains below 47%.

Such an efficiency is usually also achieved by a stationary diesel engine of a newer generation. Certainly, in this case too, the entire energy chain from oil extraction and refining to transport to the point of use should be considered.

From this point on, however, the diesel engine as a module of a heat pump shows all its valences: The heat that would otherwise be released into the environment by engine cooling (25-28%) and via the burned and expelled gases (25-30%) at high temperatures (500-700°C) is transferred to the heat exchanger, in addition to the wastewater.

A diesel engine that drives a heat pump has an efficiency – as the sum of the work and the released heat fractions divided to the supplied heat by combustion – of more than 90%! This allows it to compete with any electric motor!

The engine that has to drive the compressor of a heat pump with such a fuel in stationary operation does not necessarily have to be a diesel. For this purpose, a spark-ignited-, a Wankel, a Stirling engine or a gas turbine can also be used, depending on the technical conditions and coupling requirements to other modules.

The heat pumps with wastewater use become particularly efficient when the heat flow exceeds 100 kilowatts, for example in residential districts, industrial buildings and shopping centers. To provide all the heat required for space heating and for hot water in such a building complex in addition to the heat pump, boilers with burners are also provided, which are supplied with the same fuel as the heat pump engine.

Compared to a sole boiler heating system with gas burner chamber, carbon dioxide emissions are reduced by 45% when using a heat pump with an electric motor, and by as much as 60% with a gas spark-ignited engine instead of an electric motor! [2]. If the engine receives biogas from a neighboring biogas plant, the heat pump can be considered CO_2-neutral. The use of methanol from industrial carbon dioxide and climate-neutral hydrogen results in an even better overall carbon dioxide balance.

The wastewater network of Berlin, for example, consists of sewers for dirty, rain and mixed water with a total length of 9,400 kilometers! And this mixture is always warm, in summer as well as in deep winter. This is a gigantic heat that has so far been almost completely lost by being transferred in the atmosphere when passing through clarification plants.

Another very useful feature of each heat pump is its alternative use as an air conditioner by reversing the circuit of the working fluid: through its conduction after compression to the low-temperature heat exchanger, the heat is transferred to the wastewater. Crossing then the relief valve the working fluid cools in such a way that it can absorb heat from the "earlier" heating circuit in the building in the upper-temperature heat exchanger.

Moreover, very efficient heat pumps can also be installed in well-equipped hotels: such a building generally dispose on indoor and outdoor pools, saunas and steam baths, for which the water must be circulated and heated. The corresponding energy consumption can be up to one million kWh per year. In a classic heating system with a burner chamber under a boiler, one hundred thousand liters of heavy fuel oil are usually burned. A heat pump supplied with the heat of the collected flows of wastewater from baths and pools appears in such a case as an ideal example of second-hand heat from primary fire!

Such solutions should indeed be used on a broad scale, especially for building heating and hot water preparation, because this is the category with the largest share of primary energy consumption on a global scale – ahead of industry, construction, cement production or transport.

15

Heat and work without fire

15.1 Photovoltaics, wind power and hydropower are not enough

„Without fire" is equated by the opponents of combustion engines of all kinds with "without carbon dioxide“.

In fact, carbon-containing fuels have so far been used for combustion: *coal, petroleum products such as gasoline, kerosene, diesel fuel, heavy fuel oil, methanol, ethanol and natural gas (methane),* the chemically exact combustion of which mainly produces carbon dioxide and water. Hydrogen can also be burned, with excellent results, as already shown (Chapter 13), even if this is consciously or unconsciously ignored. However, only water is produced chemically exactly from the combustion reaction of hydrogen.

Nevertheless, the great hopefuls of the opponents of combustion engines with regard to the desired climate neutrality are *photovoltaics*, *wind power* and, with some concerns, also hydropower. Opinions on nuclear power differ widely.

In principle following aspects must be clarified:

Photovoltaics, wind and water are not used to produce every form of energy consumed in the world, but almost exclusively electrical energy.

With photovoltaics, wind and hydropower, spaces can also be heated, water boiled, or steel produced, but their participation in this is at present very low.

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7_15

As one of the world's leading industrial nations, Germany is a revealing example of this reality, because all modern economic sectors can be found in the country's energy distribution.

Transport and industry each need around 30% of the total annual energy inflow. Households need 25%, businesses 15%.

- *Transport* currently requires, however, only *1.6% electrical energy* within this share of 30%, but 94% oil.
- *Industry* consumes about 30% electrical energy within its share of *30%* and over 55% gas and coal.
- *Households* consume no more than 20% electrical energy within their share of 25%, but 57% gas and oil.
- *Trade needs within* its share of 15% of the total annual energy inflow 39% electrical energy, but also 49% gas and oil.

Conclusion:

Electrical energy accounts for less than 17 % of Germany's total energy consumption.

On a global scale, electrical energy accounts for 15 – 17% of total energy consumption (calculated from the annual reports of the International Energy Agency 2016 - 2019).

In the production of this electrical energy, all solar systems in the world are involved with 3% compared to the burning of coal and natural gas!

The wind, for its part, accounts for 7% compared to firepower using coal and natural gas!

Photovoltaics

The average *energy flux density* of solar radiation (often referred to as intensity) at the boundary of the Earth's atmosphere is 1367 watts per square meter. Part of it penetrates into the atmosphere, other parts are scattered or reflected [1]. The energy flux density of solar radiation in the Earth's atmosphere itself fluctuates between zero and 1000 watts per square meter, depending on the region of the Earth and the time of day or season.

However, there are also scientists who calculate in simplified and idealized scenarios how much energy the sun itself supplies to the Earth annually through radiation and then divide this energy to the world energy demand of a given year. What results from this sounds sensational at first: "The sun brings us ten thousand times the energy we need!" “We must therefore invest in world-saving and money-guzzling visions, instead of polluting the world with oil, natural gas and coal!”

The energy flux density of solar radiation (watts/square meter), as an integral when multiplied with the intensities on all the radiated wavelengths (Chapter 11.4), is related to surfaces. In order to obtain a satisfactory energy flow (watts), i.e. a power, at a maximum of 1000 watts per square meter (depending on the weather, and only for the hours of the day when the sun shines), large areas are required.

Example:

On an area of 2700 hectares in China, sown with solar panels (half of the entire wine-growing area in Franconia, Germany), 850 megawatts are "harvested". As a comparison, the same power is provided by the heating oil power plant in Ingolstadt, on 37 hectares, i.e. on only 1.37% of the above-mentioned area.

The sun shines on a surface of the earth only a few hours a day, depending on the latitude – more in Havana, less in Hamburg (if it does not rain in Hamburg). In summer, the radiation intensity is greater than in winter.

Example:

A photovoltaic house system in northern Germany, planned for a maximum output of 5 kilowatts, delivers a total energy of 2,880 kWh in 6 summer months (April to September), but only 1,220 kWh in 6 winter months (October to March). The difference between the outputs in individual months shows this weather and season dependence even more clearly: In August it is 625 kWh, in January 135 kWh, but in November only 90 kWh! Throughout the year, the energy adds up to 4,000 kWh. With the maximum planned output of 5 kW, an energy of 43,200 kWh would theoretically be expected in the 8,760 hours of a year – in fact, only a tenth of this was achieved!

The cornerstones of such a system consist on photovoltaic cells, which are mainly made of silicon.

In 1839, the French physicist Becquerel stated that *"a release of (electrical) charge carriers can occur through light"*. An electron can therefore detach from an atom if it has eaten energetic photons from the sun's ray.

The upper silicon layer of a photovoltaic cell is interspersed with electron donors, usually *phosphorus atoms*. This results in an excess of electrons in the structure of the upper layer. The lower silicon layer, on the other hand, is *interspersed with boron atoms* and as a result has electron deficiency, i.e. holes in the structure of the lower layer [2].

In the intermediate layer, electrons sit in holes, but they sit like in starting blocks, ready to start somewhere as soon as there is only one impulse. And now the light beams come into play: they collide with the upper layer of the photovoltaic cell, their photons, fully charged with energy, push up to the boundary layer of the cell and give the electrons in the starting blocks the welcome impulse. The electrons hiss upwards, towards the cell surface. This movement develops as a true chain reaction, in the middle layer an electron suction is formed, the lower layer supplies electrons and thus has even more holes.

An electrical voltage is therefore created between the upper and lower layers, which can be tapped through appropriate contacts on the top and bottom. The contacts are connected to a consumer via cables, it can be a light bulb or an electric motor. The electrons from the upper layer then flow through the consumer to the lower layer and so the circuit closes again. Then the light rays with energetic photons come again through the upper layer to the boundary layer and the game begins again.

However, the process could become saturated in this vertical plane: In the upper and in the lower layers both electron abundance as well as electron deficiency in the structure have a physical limit. Then you need more such "holes" on the horizontal plane, i.e. more area with photovoltaic cells.

Photovoltaic cells are expected to deliver up to 1000 watts per square meter, corresponding to the solar radiation in the Earth's atmosphere. That would be 1 kW on a panel with 1 square meter. Unfortunately, this does not work. Even with pure monocrystalline silicon, the efficiency of the described process is not higher than 24%. So, 4.17 square meters of panels would be necessary to reach 1 kilowatt of power during a maximum solar radiation. In practice, however, it is 5 to 10 square meters, the silicon crystals are not absolutely pure, often the cheaper polycrystals are used [2].

Example:

Ten square meters of photovoltaic panels can provide on a summer day with 8 hours of strong solar radiation as much energy (8 kWh) as 1 liter of gasoline.

Both large-scale and very small photovoltaic systems are installed in the world (Fig. 15.1). A pragmatic evaluation criterion of their efficiency is the ratio of the energy collected during a year, in wind and weather, through summer and winter, through day and night, compared to the planned annual energy *(planned maximum power multiplicated with the 8,760 hours of a year)*.

Example:

In 2018, there were photovoltaic plants in the world with an ideal, planned fair-weather peak power capacity of 500,000 MW. With 8,760 hours per year, they would ideally have delivered 4,380 billion kWh. However, they only managed a total electrical energy of 600 billion kWh that year, during the actual operating hours and at the actual sun radiation. 600 billion kWh divided by 4,380 billion kWh result in an efficiency of 13.7%.

In Germany, there were photovoltaic systems with a planned peak output of 45.5 million kilowatts in the same year 2018. Over the whole year it would have been 398.58 billion kWh. In 2018, however, they only generated a total electrical energy of 45.7 billion kilowatt hours (kWh). This results in an efficiency of 11.4%. This is less than the previously shown global efficiency of 13.7% [2].

Fig. 15.1 Solar system of the West Saxon University of Zwickau, Germany

It makes sense, as many applications show [2], the construction of large photovoltaic systems in deserts and in areas with particularly strong and long-lasting solar radiation, such as Australia, Kenya, Egypt, China, Dubai, Indonesia, Nevada or Colombia.

Using short-distance power grids, they can efficiently supply the mostly existing nets in neighboring cities with electrical energy in an electricity mix, regardless of fluctuation throughout the day and depending on the weather.

In addition to the large-scale plants, however, the individual photovoltaic systems in Europe, but rather in poor regions of Africa, Asia or South America, where people still have to make do without electricity, appear not only as efficient, but also as urgently needed.

Example:

A photovoltaic system with 35 square meters on the roof of a single-family house in Germany provides an electrical energy of 8,000-14,000 kWh per year when exposed to solar radiation, which is usually sufficient for the electric power supply of a family of four persons (but please note: for room heating and hot water, five times this energy is required, which is usually supplied by fuel combustion). It should be mentioned that due to the fluctuation of solar radiation, especially in the day-night rhythm, a power storage system is absolutely necessary. Lead-acid batteries, more recently lithium-ion batteries, as in electric cars, are usually used for this purpose.

The sun reaches the limit of the Earth's atmosphere with a charge of 1347 watts per square meter (W/m^2), but within the atmosphere only 1000 (W/m^2) remain. Panels of photovoltaic systems only absorb 100 to 200 (W/m^2) of this power. Over the year. considering all fluctuations, only 12 to 14 (W/m^2) remain. From a thousand watt to twelve watts, the efficiency abruptly drops to 1.2%.

In this case, the problem is not about efficiency per se, the sun has enough energy for an infinite time, which wait to be used. The real problem is only about the 12 to 14 watts per square meter, which bring only a small contribution to the total energy requirement of a country.

Primary energy consumption in Germany (2018) amounted to 3.58 billion MWh. The percentage share of electrical energy in this consumption was slightly less than 17%. And within this 17%, photovoltaic energy was involved with 7.1% (2018) [36].

The participation of photovoltaics in the primary energy demand of the Federal Republic of Germany is therefore around 1%!

The share of photovoltaics in electrical energy production has certainly grown from 7.1% to 8.9% from 2018 to 2020, but the share of total energy consumption remains below 2% (Fig. 15.2) [37].

Just as much electricity has been generated in Germany in recent years by burning biomass and using the heat obtained in power plants with a water vapor cycle.

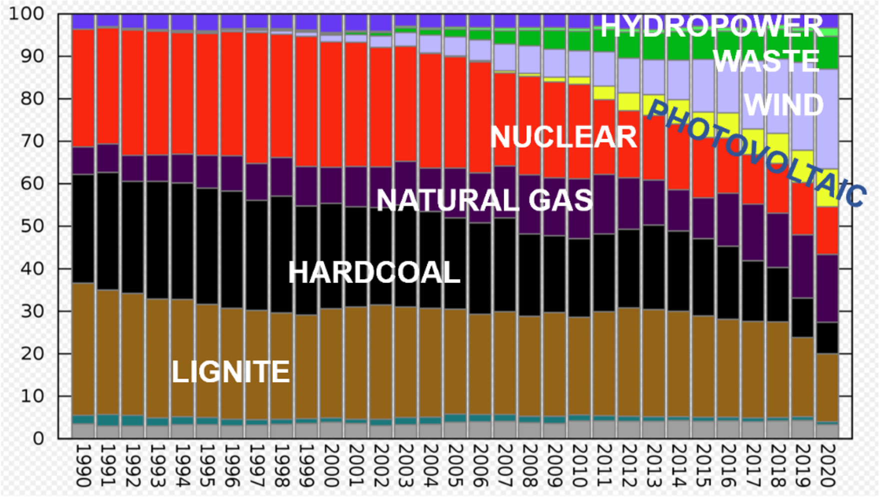

Fig. 15.2 Gross electricity generation in Germany by energy source 1990 – 2020 in percent (Source: AG Energiebilanzen, Karcher).

Wind power

The instantaneous power of a wind turbine depends on the third power of wind velocity: Between 5.4 km/h and 25 km/h, the instantaneous power increases by a hundred times [2].

This can be explained as follows: The instantaneous power of a wind turbine can be derived from the air velocity squared and the air mass flow through the wheel (kilograms per second). The air mass flow itself is the product of air density, air velocity and the air attack surface (the area described by the rotor of the wind turbine). And so, the air velocity appears for the third time in the expression of the instantaneous power! This whole theory shows a very sensitive point of the performance of a wind turbine: the wind velocity!

Fig. 15.3 Onshore-Wind Park in Texas, USA

The construction of wind turbines has been progressing very rapidly worldwide in recent years in connection with climate neutrality in energy production (Fig. 15.3). At the end of 2019, there were around 30,000 wind turbines on land (onshore) and 1,500 offshore wind turbines in Germany. At the end of 2020, there were around 200,000 onshore turbines and 5,500 offshore wind turbines worldwide with a total installed (planned) capacity of 743,000 megawatts (MW) [38].

Onshore wind turbines achieve outputs between 2 and 5 MW, the Offshore turbines generally have the better wind in terms of air density and velocity, which is why their power spectrum is also higher, at 3.6 to 8 MW.

However, it must be considered that the wind does not blow throughout the year at the wind velocity which was planned for the maximum power of a wheel. And so, the full load hours came into play: These "full load hours" during a year (Fig. 15.4), multiplied by the theoretical maximum power, must give the same energy that was achieved in actual operation with the speed-dependent load fluctuations in all 8760 hours of that year. Depending on the location and turbine design, wind turbines reach 1400 to 5000 full-load hours per year. At 8760 hours per year, this results in a utilization rate of 16% to 57% *(The global radiation efficiency in photovoltaic systems, as shown above, is 13.7%).*

Onshore wind turbine locations in Germany have reached an average of around 1640 full-load hours in recent years. It is expected that in the future the onshore plants will reach an average of 2250 full-load hours and the offshore plants 4500 full-load hours [2].

In the USA, onshore wind turbines reach 2600 - 3500 full-load hours, which corresponds to a utilization rate of 30 - 40% [2]. Recently, attempts have been made to compensate for the fluctuations in wind speed by means of "weak wind turbines" with particularly large rotor surfaces, of around 5 m^2/kW, whereby the number of full-load hours can increase to about 4000.

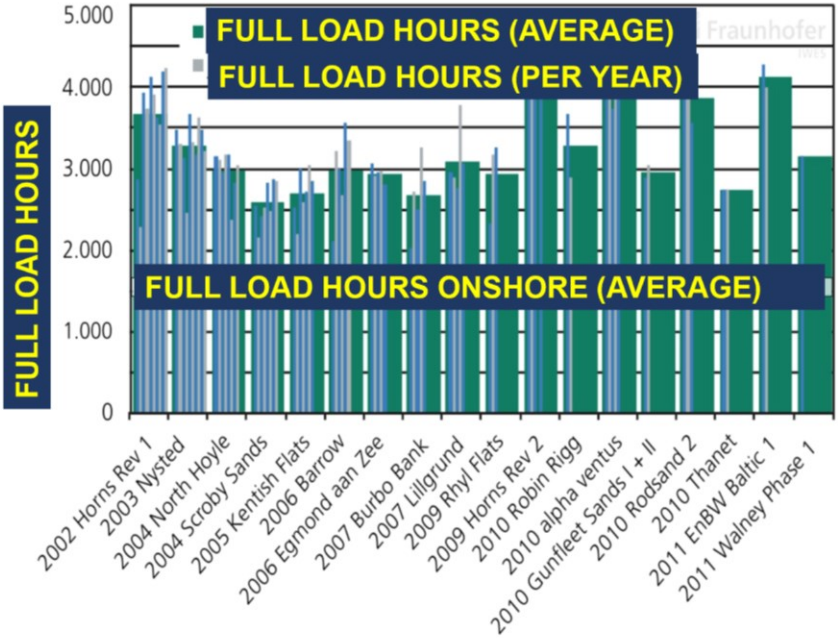

Fig. 15.4 Average full-load hours of selected offshore wind farms in the world, from a rated output of 45 MW, compared to average full-load hours of onshore wind turbines (Sources: Danish Energy Agency, BERR, Vattenfall, Fraunhofer IWES, van Pijkeren and Hoeffakker, Alpha Ventus)

A comparison of the performance yields per square meter between photovoltaic plants and wind turbines seems to be justified at this point: How could we better use the areas in the air or on earth in the future: with solar systems or with wind turbines?

The very modern wind turbine Onshore GE Model Cypress (02/2020) has a maximum planned output of 5.3 MW and a rotor diameter of 158 meters (corresponding to a wind flow area in front of the rotor of 19,596 square meters). This results in planned 265 watts per square meter. The Vensys wind turbine with a rated output of 5.6 MW and a rotor diameter of 170 meters should reach around 240 watts per square meter.

On the other hand: the photovoltaic systems reach really 100-200 watts per square meter. The efficiency of solar radiation over the year, comparable as a criterion with the full-load hours of wind turbines, was 13.7% on a global scale in 2018, 11.4% in Germany (calculated from the total photovoltaic energy and from the total photovoltaic rated output in Germany, 2018).

Compared to photovoltaic systems, wind turbines have both a 1.5 to 2 times higher area-related maximum output and a 1.5 to 2 times higher temporal efficiency (radiation efficiency/full load hours).

Wind energy generated over 8% of the world's **electrical** energy demand in 2019 (*according to the Global Wind Energy Council - GWEC)*. However, wind energy contributed only 0.6% of the world's total **primary** energy consumption (*statistical review of World Energy, 2017*).

As already mentioned, the primary energy consumption in Germany (2018) was 3.58 billion MWh. Onshore wind turbines have planned (nominal) capacities of between 2 and 5 MW.

For onshore wind turbines, an average of 2500 full-load hours is expected in northern Germany and 1800 full-load hours in the rest of the country [39].

For the entire Federal Republic of Germany, an average of 2000 full-load hours is expected. The exclusive use of very large onshore wind turbines with a planned capacity of 5 MW would result in an energy of 10,000 MWh per wind turbine over the year.

To cover Germany's entire primary energy demand, 358,000 wind turbines would be needed.

For the total area of the Federal Republic of Germany of 357,360 km^2, this would result in one wind turbine per square kilometer. The distance between each wind turbine and each of its neighbors would always be one thousand meters.

However, agriculture in the Federal Republic of Germany occupies 50% of its total area, the forests spread over 32% of the area [40].

Settlements and traffic spread to 14.5% of the area.

Where should more wind turbines be placed?

On seas and oceans, if it works!

The offshore wind farm Walney, Great Britain, consists of 2 x 51 wind turbines with 3.6 megawatts each, which occupy a total area of 73 km^2 on the water.

If it weren't for the damn nuclear power plants that everyone supposedly doesn't want and still need for their daily electricity! The *Isar 2* nuclear power plant near Munich has an output of 1485 megawatts (*according to Wikipedia: Isar nuclear power plant*) and works almost continuously (96%) at this output, which generated an energy of 12 **billion** kilowatt hours in 2019.

In the Walney offshore wind farm, the 102 wind turbines, each with 3.6 megawatts, work, while an average of 2000 full-load hours per year, resulting in an energy of 7.2 **million** kilowatt hours.

12 billion kilowatt hours with a nuclear power plant versus **7.2 million** kilowatt hours with a wind farm? That's a pretty remarkable ratio of 1667 to 1!

Hydropower

As in the case of wind turbines, hydroelectric power plants provide energy in the form of work for the generators that produce electrical energy. And just as with wind turbines, it makes more sense to record a working current (joules per second), i.e. a momentary power (watts, kilowatts). Over a certain period of time, for example over a year, these outputs can be added together at any hour, so that the entire energy (kilowatt-hour, kWh) can then be determined.

The instantaneous power in the turbine of a hydroelectric power plant is determined similarly to that in the rotor of a wind turbine. The basic elements are: The mass flow of the air or water and the mass-related energy of the respective medium (in the case of wind the kinetic energy, expressed by the speed, and for water the potential energy, represented by the drop height and by the gravitational acceleration[2].

The mass flow is given in the wind (air) as in the water, by means of density, flow cross-section and flow velocity. But there is a huge difference: Water has almost a thousand times the density compared to air, which is why the current output of a wind turbine and that of a hydropower plant appear to have different orders of magnitude [2].

Example:

The GE Cypress wind turbine has a maximum output of ***5.3*** *megawatts. The three-gorge hydropower plant in China has a maximum output of* ***22,500*** *megawatts.*

Water revealed for Homo sapiens for the production of work and later of heat, right after the fire.

The first watermill to produce electricity for house lighting was built in England in 1878. And a short time later, in 1895, the world's first large-scale hydropower plant for the production of alternating current was inaugurated above Niagara Falls. The installed capacity reached more than 78 MW after a few years. In 1961, this hydroelectric power plant was replaced by a new one with a capacity of 2,400 megawatts.

Water, like air, has an energy that essentially consists of three components: internal energy expressed by temperature, pumping/potential energy expressed by pressure/drop height, and kinetic energy expressed by velocity. As long as the considered amount of water or air does not exchange energy in the form of *heat and work* with the environment, the total energy remains constant. However, the three components mentioned above can exchange energy between each other during a process (Chapter 7.2).

For the qualitative evaluation of processes of all kinds, whether in wind turbines or in water turbines, the energy, including each of its three main components, is generally related to the mass (kilograms) of the respective working medium, water or air. This is also advantageous because water, like air, does not appear as a solid mass, but as a mass flow (kilograms per second). Multiplying the mass flow by the mass-related energy, this results in an energy flow, which is nothing else than the momentary power of the respective working medium in the wind turbine or in the air turbine.

From this point on, a fascinating game begins for the water on the way to the turbine [2]: In such a configuration, no further energy is actually exchanged with the environment, neither as heat nor as work. The water falls from the mountain because it has a potential energy at the given drop height. This potential energy is largely converted into velocity (i.e. kinetic energy), a little pressure (potential energy) remains, depending on the conditions on the way. The internal energy, expressed by the temperature of the water, generally remains unaffected by this way, apart from some friction, which is converted into frictional heat, which is usually given to the environment, as a loss.

Now the water from the mountain could fall directly into the turbine. However, it would be more advisable to first collect it in a basin, for some hard times when nothing comes from the mountain. A downpipe can then be built between the basin and the turbine.

The power has the same roots for electrics, wind and water flow: an intensity (*electric current, mass flow of air or water*) and a potential (*electrical voltage, height difference, pressure gradient, speed difference*).

This is also how the hydropower plants are built, either with more emphasis on mass flow or more potential.

However, not all hydropower plants are similar:

Run-of-river power plants are generally built in flowing waters, with a barrage at a weir, with the mass flow being the same at inflow and outflow. The potential due to a drop height is usually low, up to 15 meters. In such a case the power is determined by the mass flow, as in the hydroelectric power plant above the Niagara Falls.

Storage power plants get the water from basins. Between the basin, at a certain depth that provides a pressure potential, and the turbine, a diagonal water downpipe with a defined drop height is built. This is a combination between the pressure potential at the inflow point and the velocity potential in the pipe.

The power plant with the largest drop height in the world is located in Naturno, South Tyrol: it is a proud 1,150 meters! The plant has an output of 180 MW.

Pumped storage power plants demonstrate a special management of electrical energy: They consist of two water basins at different heights, between which a downpipe system is built. When the economy of the near or far surrounding area needs electric energy, the water flows from the full upper basin via the turbines into the rather empty lower basin, thus driving the power generators to cover the peak loads. After a while the water level is low in the upper basin and high in the lower basin. This usually happens at night, when not much electricity is needed. During the night, the water is then pumped up from the lower to the upper basin, with the help of the otherwise unused electricity from the grid.

The largest hydropower plant in the world "Three Gorges", with a basin length of 663 kilometers, was built in China (finished in 2008) and has a rated output of 22,500 MW. The second largest plant, also in China, planned for 16,000 megawatts, was completed in 2021. A total of a quarter of the world's hydropower capacity is installed in China. Brazil and Paraguay have jointly built a hydropower plant with 14,000 MW on the Rio Paraná, which is currently the third largest in the world.

The most important hydropower nation in Europe is Norway with 1500 plants (2019), which ensure 93.5% of the country's electrical energy.

Water provides about 17% of the world's electrical energy. Hydropower plants, on the other hand, have held first place in electricity generation from renewable energies for many years. In 2015, almost 70% of the world's clean electricity was from water, ahead of wind power at 15.5%. Photovoltaics managed just 5%. However, the economic, technical and ecological developments in the world are leading to tendencies that sometimes seem unexpected: In the period 2015-2019, the share of wind power in world electricity has steadily increased and reached almost 21%. Photovoltaics has moved in the same direction during this period, doubling to more than 10% in 2019.

Nevertheless, the participation of hydropower shows a significant decline from the 70% to about 58% [2]. Who doesn't like the water?

The investment costs are very high and would only make such a plant profitable if these costs were covered by the price of electricity. But if the state is behind it for ecological reasons, like China, the situation is quite different.

Hydropower plants are, at first glance, atmosphere-friendly because the energy they produce does not generate carbon dioxide emissions. But only for this reason they are not necessarily nature-friendly. Basins are a massive intervention in the groundwater balance. As a result, the rivers are out of balance, flora and fauna are impaired. For the construction of dams, entire human places are often relocated.

For a total output considered, a number of micro-hydropower plants can be more ecologically compatible, less dangerous and more cost-effective than a single, large hydropower plant with a large dam, with a large basin and with a tall drop height.

Recently, micro hydropower plants have been developed for river sites with low hydropower potential [2]. The small mobile power plants work without accumulating water. Only a water drop height of at least 2.5 meters is necessary, with a water width of five meters and a flow speed of over 5 km/h. For this purpose, new horizontal waterwheel variants are being developed. The micro-hydropower plants can also be set up as a fleet, which opens up promising paths!

15.2 The Last Weapon: Nuclear Power

Nuclear power is again of interest in relationship with energy for the world! Closing one's eyes and turning off the mind by rejecting them **in principle** is also not expedient. The so-called "nuclear power" (correct would be, as well as for wind and water: nuclear energy) brings in comparison with all other energy sources the incomparably largest energy with the lowest mass input. Neither carbon dioxide nor other substances are emitted, they don´t need much space, the costs per unit of power are more manageable than those of gigantic dams and endless basins. Admittedly, after the terrible disasters of Chernobyl and

Fukushima, nuclear power appears to be the final weapon when searching energy for the world. Nuclear energy would ensure by itself all energy for the world.

If the high-tech creating nations of the world no longer wanted to use nuclear energy in plants, albeit a kind of precision weapons, they would put this technology in the hands of desperate energy-hungry people who have only rudimentary manufacturing technologies.

Won't the energy-hungry build nuclear power plants just because the rich, highly industrialized countries are no longer building them?

As if! The countries which need much more development will build nuclear power plants, but rickety, unsafe, dangerous. And if radioactive radiation were to be produced at the place of production or use?

Could be possible to quarantine radiation particles from other countries on the border of Germany or Italy, such as persons infected with the coronavirus?!

The benefits of nuclear power plants are clear, the hazards must be precisely measured and evaluated, and their avoidance or circumvention measures should be precisely formulated, implemented or prepared.

Tsunamis, floods, earthquakes, terrorist attacks, cyber-attacks and plane crashes can also menace large dams, chemical plants, battery plants and hydrogen production plants, also with catastrophic consequences.

In 2020, 442 nuclear power plants with a total capacity of almost 400,000 megawatts are in operation all over the world, 95 of them in the USA, 56 in France 48 in China, 38 in Russia, 22 in India, 5 in Pakistan [2].

In principle, there is no difference between a nuclear power plant and a coal-fired power plant in terms of the working fluid course within the thermodynamic cycle and of the machine modules. The only difference is the way to heat the working fluid which consists on water.

In the nuclear power plant as in the coal-fired power plant, the water is heated as a working fluid in a boiler until vaporization, the steam is then expanded in a turbine that is mechanically connected to the power generator and performs work in the process. The steam after the turbine is cooled in a heat exchanger until it becomes liquid water again. The water is brought back to the boiler by means of a pump and the process starts again (Fig. 15.5).

The water in the boiler, as a working fluid, can be heated with wood, with coal, with heavy fuel oil, with gasoline, with gas, with schnapps or using an electric heating spiral. What do the fuel elements in the reactor of the nuclear power plant so differently? They also only produce heat, for heating the water in the boiler, but in a different way.

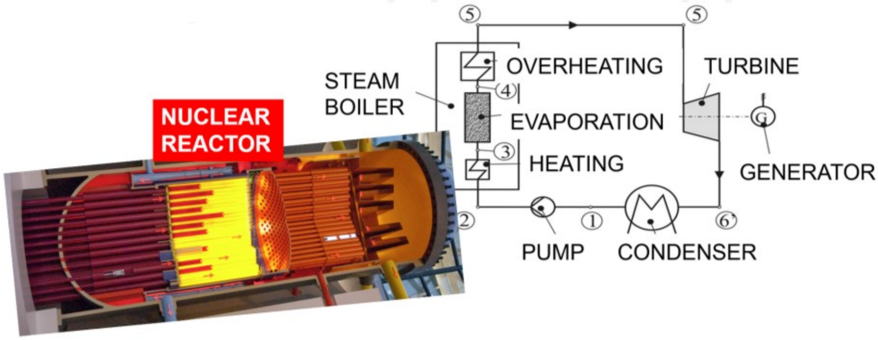

Fig. 15.5 Schematic of a nuclear power plant, as a combination of a nuclear reactor with a power plant with a steam turbine (Fig. 3.3)

The fuel elements are a bundle of thin fuel rods encased in water. However, in one of the common power plant embodiments, the power plant with pressurized water reactor (easier to understand as an example in this context), this is an "own water", not the water as a working medium in the cycle of the power plant, as shown above. The fuel rods contain uranium, more precisely uranium oxide. There, a controlled nuclear fission takes place, in which the atomic nuclei are bombarded by free-running small particles, called neutrons, and broken down into splinters. The newly formed splinters fly explosively apart, this is similar to chopping wood. With their enormously increased speed, the splinters rub against the liquid in which they are trapped. This is like the meteorites that fall on Earth, they rub against the air in the atmosphere until the temperature at the point of contact reaches thousands of degrees, burning the meteorite itself. The hot liquid transfers a large part of the heat to the water in the boiler of the power plant, like the rods of an electric heater. And that's it!

The energy of the uranium used is much greater than the heating value of wood, coal, gas or heavy fuel oil, with which the boiler could also be heated. One kilogram of uranium has as much energy as 12,600 liters of crude oil or 18,900 kilograms of hard coal. This can generate over 40 megawatt hours of electricity. A fuel element remains in the reactor for about three years. After that, there is a reprocessing to plutonium, which in turn also gives off a lot of energy.

And then? Of all the world's nuclear power plants currently in operation, about 12,000 tons of radioactive waste are generated each year, which also contains plutonium [2].

In addition to the problem of reactor safety during its function, there is also the disposal and final storage of radioactive wasted components, such as fission products, and incubated trans uranium such as plutonium. These components are still active, although not with the same intensity as in the reactor. However, they radiate the energy generated during further fission to wavelengths in the X-ray range of the spectrum, which can be carcinogenic to death for humans and animals. These post-reactions last a very long time, between a few months and a few thousand years, with iodine isotopes it is even millions of years. Reprocessing would theoretically be possible, but it would "only" shorten the activity of such proportions to a few hundred years.

The final disposal of such “nuclear waste" remains a problem that has not really been solved worldwide. Common materials are not able to bind or insulate such substances permanently. They are often melted into glass, incorporated into ceramics, poured into concrete and stored in mines, whereby the mountain rock must ensure the safe containment of radioactive materials. The infiltration of water into such repositories would be catastrophic, because several types of dangerous chemical reactions could occur as a result. Salt domes, granite and clay rock are currently being discussed as final repositories. The storage of radioactive material in the open air is of course strictly prohibited by law in Western Europe. However, the "export" of such nuclear waste to Siberia or Kyrgyzstan, where the contaminated barrels may be placed in parking lots and other areas unader the open sky, is not prohibited. In 2009, the wreck of a large freighter with 120 barrels of nuclear waste on board was discovered in the Mediterranean. According to the subsequent investigation, at least another 32 ships with similar cargo were sunk in the Mediterranean [2].

Scenarios for the final disposal of all the world's nuclear waste under the Antarctic ice sheet are also being developed. It couldn't be more stupid! Or is it?

Disposal in space is the new booze idea of "experts" from science, business and politics! Simply store on asteroids and on other planets – perhaps also in parking lots there, as in Siberia. But the foolhardiest idea is to shoot the nuclear waste directly into the sun, so it would actually be away from our biosphere! What we then get from the dear sun as a receipt for our biosphere and for our flora and fauna, so far the spinners had not come!

Photovoltaics, wind, water and nuclear energy can complement the fire, but not replace it

Photovoltaics, wind and water bring climate-neutral contingents for the world's primary energy consumption, but these fractions are still much too low. An intensive or extensive outbreak would hardly be justified or expected. Nuclear energy has sufficient potential, but it hides serious dangers for the human world.

Let the fire still burn, inserting the experience that humans gained over thousands of years!

Let us provide the fire with exclusively climate-neutral fuels and with machines and systems that work very sparingly! (Fig. 15.6)

Fire is not a monster!

Fig. 15.6 Fire for work and heat in an internal combustion engine

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Summary of soundbites

Part I

Fire is the outer manifestation of combustion, as a chemical reaction between a fuel and oxygen. It is basically characterized by thermal radiation and occasionally by light radiation (as a flame of gases and vapors or as embers of a solid substance).

The newly developed, controlled compression ignition strategies for gasoline and diesel engines lead to efficiencies in the range of 50% and push the emissions of nitrogen oxides and other pollutants below the legal limits, even without catalysts

A human is the only being in the fauna of the earth who processes most of his food by fire!

Not the fire, but what you still burn is responsible for the increase in the proportion of carbon dioxide in the atmosphere.

Replacing fire from the entire energy production of a country or industry with electricity remains a utopia. You just have to offer the fire a climate-neutral food!

The production of one ton of iron in the electric furnace "costs" up to 2,500 kilowatt-hours.

The production of one ton of aluminum by electro-lysis “costs” an average of 16,000 kilowatt-hours, which is six to seven times more than a ton of iron produced in the electric furnace.

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7

Temperature is a perceptible and measurable expression of the microscopic movement of particles in a body or medium which exists in the macroscopic world. Temperature is not a real, physical quantity, such as a length (in meters) or a duration (in seconds), but an indirect indicator of particle energy [1].

Heat is a form of energy that is transferred between two systems of different temperatures as a result of their thermal contact. Heat appears only during an energy exchange, but it cannot be stored.

Work, similarly to heat, is a form of energy that is transferred between two systems due to a pressure difference, at the site of their mechanical, freely moving contact. Work appears only during an energy exchange, but it cannot be stored.

In addition to its *internal energy*, a flowing medium has a *pumping energy*, expressed in pressure and density, and, in some situations, a *kinetic energy*, expressed in macroscopic flow velocity. The collective term for all these energy components is defined as "*enthalpy*", being sometimes named also “total enthalpy” or stagnation enthalpy”, in respect to the contained part of kinetic energy.

For the basic calculation of pressures and temperatures in such a process, as well as of the exchange of heat and work, it is usual to consider it as simply adding heat to the air in the engine, regardless of the fuel and the chemical reaction itself.

The thermal efficiency of a heat engine is defined as the ratio of the *work* done by the machine to the *heat* supplied by combustion of a mixture of air and fuel.

In a turbomachinery (gas turbine), all process stages, from air intake and compression to combustion, expansion and exhaust of the burned gas take place simultaneously, everyone in a functional module developed and optimized for this purpose.

A process-related revolution is usually more efficient than a construction-related, often very cumbersome evolution.

People have been dreaming of *nuclear fusion* like in the sun for a long time. It is only uncertain how they would deal with it if they could control it.

A fuel contains one or more of the following elements: *carbon, hydrogen, sulfur, oxygen, ballast.* Depending on which of these elements are present in a fuel, its complete combustion with oxygen from the air results in: *carbon dioxide and water vapour,* in some cases also *sulphur dioxide*.

99,7 % of Brazil's sugar cane plantations are located on plains in the southeastern region of Sao Paolo, which is at least 2,000 kilometers from Amazon's tropical forest, where the climate is rather unsuitable for sugar cane.

The eFuels are alcohols made from carbon dioxide and green hydrogen. By recycling carbon dioxide between industry, heat engines and the atmosphere, they could save the existence of all internal combustion engines currently operating in the world!

The utilization of hydrogen, either by combustion in a heat engine or by proton exchange and thus generating electricity in a fuel cell, leads back to the original water.

Combustion remains the mother of all chemical reactions!

The influence of the burning of fossil fuels on the Earth's atmosphere is currently regarded as an existential criterion for the heat-consuming economy.

Without the natural greenhouse effect caused by water vapor and naturally present trace gases, the average temperature of the Earth's atmosphere would drop by 33 °C, i.e. to *minus* 18 °C.

The combustion of one kilogram of gasoline or diesel produces around 3.1 kilograms of carbon dioxide. Burning one kilogram of coal yields 3.7 kilograms of the same greenhouse gas, while burning one kilogram of natural gas results in only 2.7 kilograms of carbon dioxide.

From now on, the people of all countries should burn climate neutral fuels and couple the various processes in power plants, machines, heating systems and combustion engines according to the most effective rules of thermodynamics.

According to Murphy's laws, what must not happen always happens: A free-floating nitrogen atom combines with a free-floating oxygen atom in a novel molecule: nitric oxide. Sometimes two oxygen atoms want to meet a nitrogen, they then form a stick dioxide. Or two to three and two to four. And so, the catastrophe of the modern world arises: the nitrogen oxides!

When fine particles enter with the inhaled air into the alveoli, they cause inflammation of the surfaces or water retention. It is worth noting that even inhaled water droplets with sizes around 0.1 to 2.5 microns act as particles!

Part II

An exchange of energy between a system and its environment leads to a change of the thermodynamic properties of the working medium. Thermodynamic properties or state variables include *pressure, temperature and volume.*

Using deterministic methods, from the analysis of the behavior of a single individual, it is practically impossible to derive the behavioral characteristics of an entire society.

Phenomenology can be defined as a summary of exclusively experimentally gained knowledge for as many similar processes as possible with subsequent derivation and formulation of laws and recording of such laws in short, concise formulas, if possible.

A *state* characterizes the equilibrium of a system on a macroscopic scale, which is based on a dynamic equilibrium on a microscopic scale.
A *state variable* is a macroscopic property of the system in a state.

The first law of thermodynamics – general form
Between the subsystems of an energetically isolated system, an energy exchange can take place in such a way that the energy of individual subsystems changes. However, the total energy of the system, as the sum of the energies of the subsystems, remains constant.

The First Law – Exchange System-Environment
During the energy exchange between a system and its environment, for example as heat or work, the sum of all forms of energy of the system and the environment remains constant.

The First Law – State Changes in Closed Systems
The exchange of heat and work between a closed system and its environment during a change of state corresponds to the variation of its internal energy.

The First Law – State Changes in Open Systems
The exchange of heat and work between an open system and its environment during a change of state corresponds to the variation of its enthalpy.

The specific heat capacity of a substance, which can be also air, is defined as the energy (heat) required to increase the temperature of its unit of mass (1 kg) by 1 Kelvin.

Any form of irreversibility costs energy from the environment of the respective process.

A natural process always proceeds in the direction of equilibrium.

Formulations of the Second Law of Thermodynamics:

Heat can never pass on its own from a system with low temperature to a system with higher temperature. (Clausius, 1822-1888)

A process in which the conversion of the heat of a single source with constant temperature into work is not possible. (Thompson, 1753-1814)

Near the equilibrium state of a homogeneous system, there are states that can never be achieved without heat exchange. (Caratherdory, 1873-1950)

All processes where friction occurs are irreversible. (Planck, 1858-1947)

All natural processes are irreversible. (Baehr, 1928-2014*)*

The thermal efficiency of an ideal Carnot cycle carried out with air depends only on the extreme temperatures during heat exchange on hot and on cold side.

The entropy of a system becomes greater during an irreversible change of state than the entropy, which would be caused by a utilizable energy conversion.
Reason: The pursuit of a state of equilibrium, which characterizes every natural process, is always bound to an energy dissipation.

In our world there are an infinite number of compensation potentials that cannot or must not be transformed because of given conditions or circumstances.
The spirit is given by the activation of the potentials, or, may be, by the initial splitting of cause and effect.

The heat to be expected from the combustion of a conventional fuel with air remains almost the same for the same mass of mixture, regardless of the type of fuel.

For the sake of high thermal efficiency, a piston engine should achieve compression like a diesel and combustion like a gasoline engine

The main advantage of a gas turbine compared to a piston engine is the combustion chamber. The continuously injected fuel jet cannot reach any combustion chamber wall: if the jet is too long, the chamber can also be prolonged. The time for atomization and evaporation of the jet is not a problem because the jet flow is continually

Let's keep all the military jets in the world on the ground and replace fire with water for the people which need cool heads!

A flame is a gas mixture during a combustion process.

The method that allows modeling on the basis of experimentally obtained data for application in processes other than the measured ones is called similarity theory [1].

Part III

The fire will be preserved for thermal machines and plants, but from now on all fossil energy carriers are to be banned completely: *coal, petroleum derivatives and natural gas*.

It is really the last chance in terms of saving the world's climate: but instead of trying to create a model region in the prosperous and technically superior Europe, it would be imperatively to save so many poor countries in Africa, Asia and South America from the oil, gas and coal plague!

To create miracles, the fire needs, like humans, good food and a wholesome digestion.

It may be that the combustion engines or the “burners”, above all, the discredited diesel engines will be banned from the road traffic. But on the seas and oceans of the world, the real conditions force a different course of action.

Not only the "green" methanol, but also the hydrogen is currently finding its way into internal combustion engines as a fuel for the future.

Although combined cycle power plants with climate-neutral fuel could be replaced by a number of wind turbines, more than 400 of them would be needed to replace a single power plant. And they primarily only supply electricity, but no heat.

A second-hand fire made of garbage not only helps to relieve overcrowded landfills. It also generates electricity and heat, with a considerable share, in addition to the central supply networks.

Automotive drives with biogas-powered internal combustion engines have particularly great potential in terms of globally reducing carbon dioxide emissions.

An ideal internal combustion engine is designed to eat biogas from waste to generate heat that is converted into a slightly less work, whereby four times more heat than the original one arises!

A diesel engine that drives a heat pump has an efficiency – as the sum of the work and the released heat fractions divided to the supplied heat by combustion – of more than 90%! This allows it to compete with any electric motor!

Photovoltaics, wind and water are not used to produce every form of energy consumed in the world, but almost exclusively electrical energy.

Electrical energy accounts for less than 17 % of Germany's total energy consumption.

The sun reaches the limit of the Earth's atmosphere with a charge of 1347 watts per square meter (W/m^2), but within the atmosphere only 1000 (W/m^2) remain. Panels of photovoltaic systems only absorb 100 to 200 (W/m^2) of this power. Over the year. considering all fluctuations, only 12 to 14 (W/m^2) remain. From a thousand watt to twelve watts, the efficiency abruptly drops to 1.2%.

The instantaneous power of a wind turbine depends on the third power of wind velocity: Between 5.4 km/h and 25 km/h, the instantaneous power increases by a hundred times [2].

Compared to photovoltaic systems, wind turbines have both a 1.5 to 2 times higher area-related maximum output and a 1.5 to 2 times higher temporal efficiency (radiation efficiency/full load hours).

If the high-tech creating nations of the world no longer wanted to use nuclear energy in plants, albeit a kind of precision weapons, they would put this technology in the hands of desperate energy-hungry people who have only rudimentary manufacturing technologies.

In principle, there is no difference between a nuclear power plant and a coal-fired power plant in terms of the working fluid course within the thermodynamic cycle and of the machine modules. The only difference is the way to heat the working fluid which consists on water.

Let the fire still burn, inserting the experience that humans gained over thousands of years!

Glossary

C. Stan, *Future Fire Forms*, https://doi.org/10.1007/978-3-031-12081-7