6. Heat cycles and their realizations

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In previous articles 4. Use of wind energy, 5. Use of water gradient and 2. Sun radiation as source of energy are shown equipments and machines which can transform kinetic energy of wind, potential energy of water gradient and electromagnetic radiation to electricity or work. But there are equipments which can transform heat to work or to electricity. Inside these equipments are performed heat cycles(1). Why is possible this transformation of energy and essential terms are descripted in the article 43. Engineering thermomechanics. Parallely to the heat cycles which are transformed heat to work there are heat cycles which use work for increasing temperature of working fluid e.g. a refrigeration cycle.

(1)*Direct transformation of heat to electricity*
The heat is can transform direct to electricity through thermoelectric or thermal emission equipments [8, p. 854].

In this article I describe only the most used heat cycles respectively only their ideal versions. The **ideal heat cycle** is composed from only reversible thermodynamic processes. Nevertheless these perfect cycles can not be performed in praxis only can be performed approximately (there are technical even investment limits) these cycles we can call **real heat cycles**. For example compare the Stirling cycle with a real cycle of the Stirling engine. The real cycle of the Stirling engine is function losses and use type of mechanism of piston, it is evident from real shape of Stirling engine cycle which is shown in article 36. Losses in Stirling engines. The real cycles are some similar the ideal cycles if their realization is very tardy and their losses are negligible. Therefore heat cycles which are composed only reversible thermodynamic process are called **compared heat cycles**. The main reason for reached high similarity the real cycle with ideal cycle is an increasing efficiency of heat cycle.

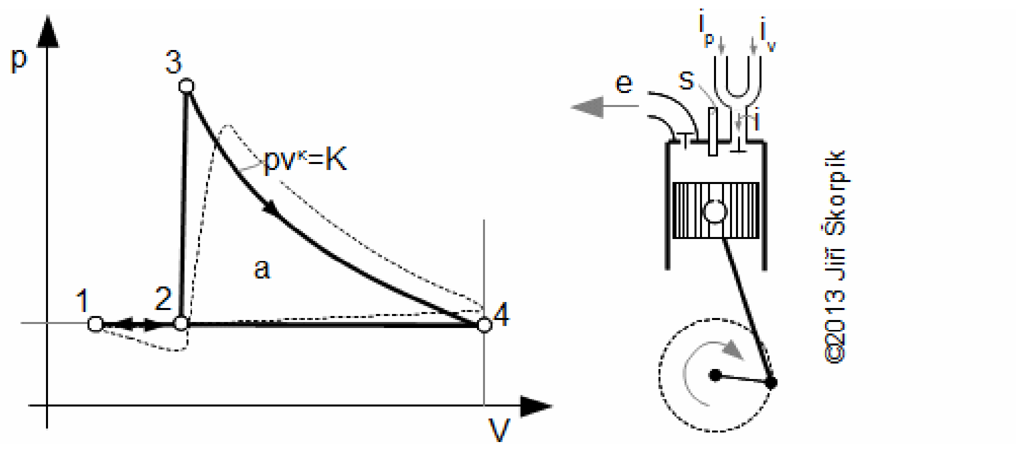
The heat cycles are drawn in p-V diagrams or in T-s diagrams, in which are better evidently of energy flows for calculation energy balance of cycle.

Cycles of internal combustion engines

This term is used for cycles of piston machines, in which burning of fuel mix. These cycles are performed inside working volume - cylinder, therefore term **internal combustion engine**. The most frequently in technician world is can meet with modifications of three cycles: Lenoir cycle, Otto cycle and diesel cycle which are named by its inventors Jean Lenoir, Nikolaus Otto and Rudolf Diesel:

Lenoir cycle

It is the cycle of gas reciprocating engine. The cycle is performed during one turn of the shaft at step by step the suction of air and flammable gas, the ignition and burning, expansion of hot exhaust gas and displaced of exhaust gas from the cylinder:



1.976 *p-v diagram of the Lenoir cycle.*
i inlet; **e** exhaust; $\mathbf{i_p}$ suction of fuel or injection if fuel is liquid; $\mathbf{i_v}$ suction of air; **s** spark plug. **p** [Pa] pressure; **V** [m^3] volume; **κ** [-] heat capacity ratio of working gas inside cylinder; **a** [$J\cdot kg^{-1}$] specific work of cycle; **K** constant. The real change of state of working gas is drawn by dashed line.

An ideal realization of the Lenoir cycle is composed by four reversible thermodynamic processes(2, 3, 4, 5):

(2)*The suction*
The suction proceed on part *1-2* of the p-V diagram, it means during move of the piston from the top dead center to the position *2*.

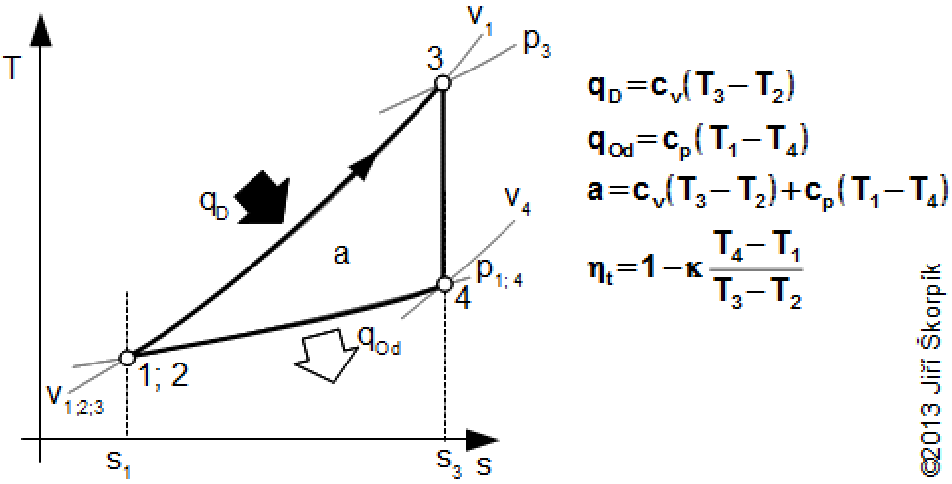
(3)*The burning*
In the state *2* is closed suction valve *i* and through the spark plug is ignited the fuel mix inside cylinder. The pressure is isochoric increasing during the burning at which arises hot exhaust gas. For ideal case this process (between point *2-3*) is at no-move of piston.

(4)*The expansion*
From maximum pressure in state *3* the hot exhaust gas isentropic expands to state *4*. At state *4* the piston reaches its bottom dead position.

(5)*The exhaust*
The outlet of the exhaust gas is performed through the piston motion from its bottom dead position *4* to its top death position *1*. In this state is one cycle closed and it can be repeat.

The changes of states of the working fluid inside real engine are different from the changes of ideal cycle. These differences are caused by discontinuous motion of the piston and progress and speed of the burning.

This type of cycle is performed inside engines which are called Lenoir engines. Their first version contained a slide valve and as fuel has been used coal gas with atmospheric pressure which was mixed with air.

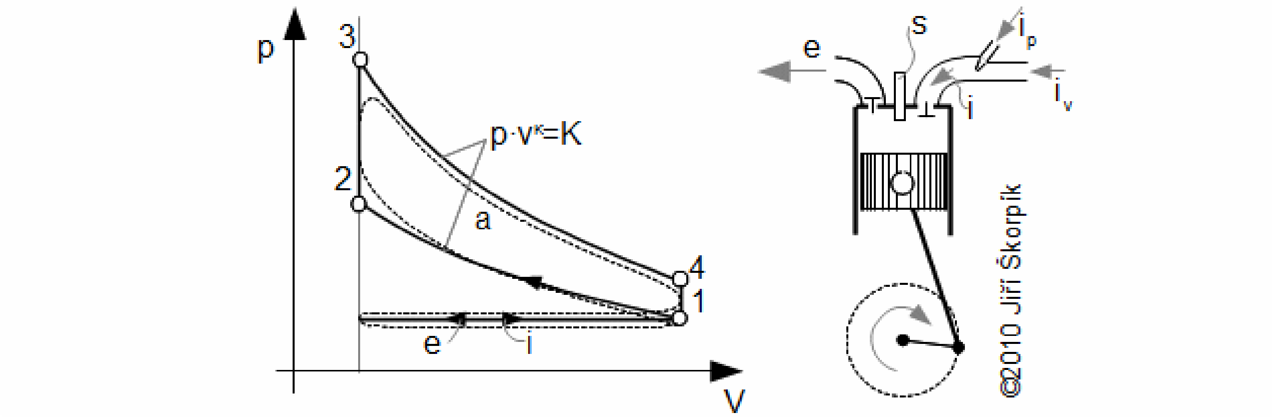


2.977 *T-s diagram of the Lenoir cycle and essential equations for case its ideal realization.*
T [K] absolute temperature; **s** [J·kg^{-1}·K^{-1}] specific entropy; $\mathbf{q_D}$ [J·kg^{-1}·K^{-1}] specific input heat of cycle; $\mathbf{q_{Od}}$ [J·kg^{-1}·K^{-1}] specific rejection heat of cycle; **v** [m^3·kg^{-1}] specific volume; $\mathbf{c_v}$ [J·kg^{-1}·K^{-1}] specific heat capacity at volume constant (in this case it is assumed as constant but in real conditions it may change under burning); $\mathbf{c_p}$ [J·kg^{-1}·K^{-1}] specific heat capacity at pressure constant (in this case it is assumed as constant but in real conditions it may change under burning); $\boldsymbol{\eta_t}$ [-] heat efficiency of cycle. These equations has been derived from first law of thermodynamics for closed system because the changes of state of the working gas are performed inside closed cylinder. The derivation of equations for energy balance of the Lenoir cycle is shown in the Appendix 977.

Because the heat is produced inside the Lenoir engine through exothermic chemical reaction during burning fuel mix is used term an internal combustion engine. Because at the exit cycle is changed the filling of the working gas inside the cylinder, so is used term for a **open cycle**. During calculation of the real Lenoir engine cycle is necessary take in account changes thermodynamic properties of the working gas during the burning.

Otto (spark ignition) cycle

The ideal Otto cycle is composed by four reversible thermodynamic processes which are performed inside a cylinder with a piston and two valves (suction and exhaust valve). One cycle is performed during two strokes of the piston (four machine cycles). As working fluid is used a flammable mix usually the mix of air and vapor of fuel:

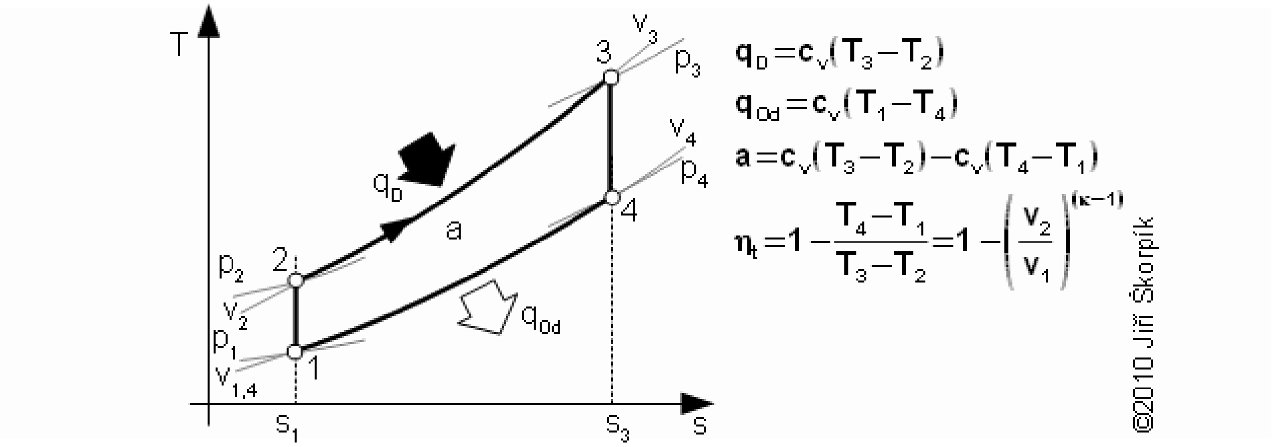


3.617 *A p-v diagram of the Otto cycle and one its possible realization.*
i suction of working mix (the piston is moved to a bottom dead position and suction valve is open); **1-2** isentropic compression of working mix (the suction valve is closed, **pressure ratio** is in interval *8* up *13* along fuel type [7, p. 11] – ratio between maximum and minimum volume of cylinder), state *2* must be in relation to pressure and temperature which is lower than flash point but parallelly must reach burning temperature; **2-3** burning of working mix - working mix is ignited through the spark plug in state *2*, this working mix very quick burn at increasing the temperature and pressure on state *3*. Ideal burning is isochoric process – the piston is not moved; **3-4** expansion of hot combustion gases - hot combustion gases expand from state *3* to state *4*, during the expansion gases act on piston by force (piston is done work); **4-1** exhaust - exhaust valve is open in state *4* and the combustion gases are exhausted to the exhaust. The cycle is closed at displacement of combustion gases from the cylinder through open exhaust valve *e* by the piston during its motion to the top dead position. The cycle can be repeated in this point.

For ideal realization this cycle would have needed discontinuous movement of the piston, but this mechanism is not suitable for practical use and the move of the piston is performed continuously through a crankshaft mechanism. It means the isochoric processes on sections *1-3* and *4 – 1* can not be perfectly performed. In real situation the fuel mix is ignited in front of top dead position of the piston during compression (so called **ignition timing** in front of point *2*), and the opening exhaust valve is done in front of the bottom dead position of the piston during expansion of the combustion gases. The real cycle are influenced also by the valve and shape suction and exhaust pipes, in which arises pressure drop, which decreases work of the cycle.

There are other realization where the cycle is apportioned only to two machine cycles. It means during motion of the piston to the bottom dead position proceeds gradually the combustion of fuel mix, the expansion and open of the exhaust valve and the exhaust. At motion of the piston to its top dead position are at start opened the exhaust and the suction valves. The suction of fuel mix is through a underpressure of the exhaust gas inside the cylinder. This underpressure is done at cooling of the exhaust gas. Following a closure of the suction valve and compression of the fuel mix. In front of the top position of the piston is ignited the fuel mix. In this case of two machine cycles is the exhaust valve localized at near the bottom dead position of the piston. These types of engines are simpler and have higher power output at the same speed, but usually worse the efficiency than four machine cycle engines.

The first realization this cycle was in Otto's engine for combustion liquid and gas fuels.

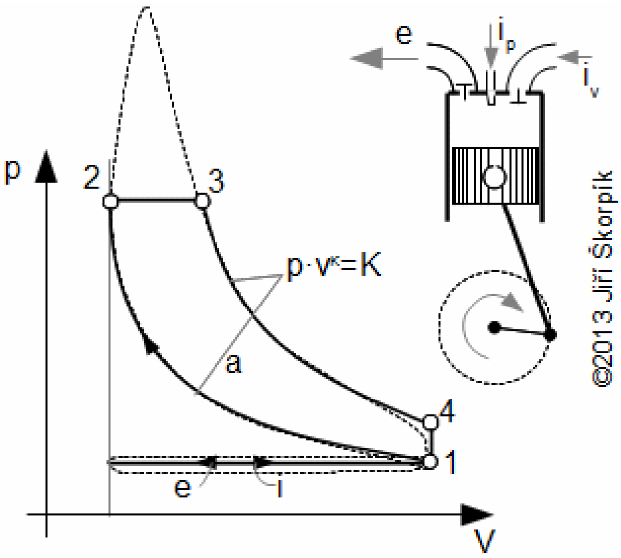


$$q_D = c_v(T_3 - T_2)$$
$$q_{Od} = c_v(T_1 - T_4)$$
$$a = c_v(T_3 - T_2) - c_v(T_4 - T_1)$$
$$\eta_t = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \left(\frac{v_2}{v_1}\right)^{(\kappa - 1)}$$

4.620 *T-s diagram of the Otto cycle and essential equation for case its ideal realization*
At derivation of essentials equation is can used first law thermodynamic equation for closed system because at ideal case the thermodynamic processes are performed in closed cylinder. The derivation of equation for energy balance of the Otto cycle is shown the Appendix 620.

Diesel cycle

A Diesel cycle is divided on four machine cycles as the Otto cycle. Typical for the Diesel cycle is higher pressure ratio, isobaric heating of the working fluid and direct injection the fuel to the cylinder in front of the end of compression:



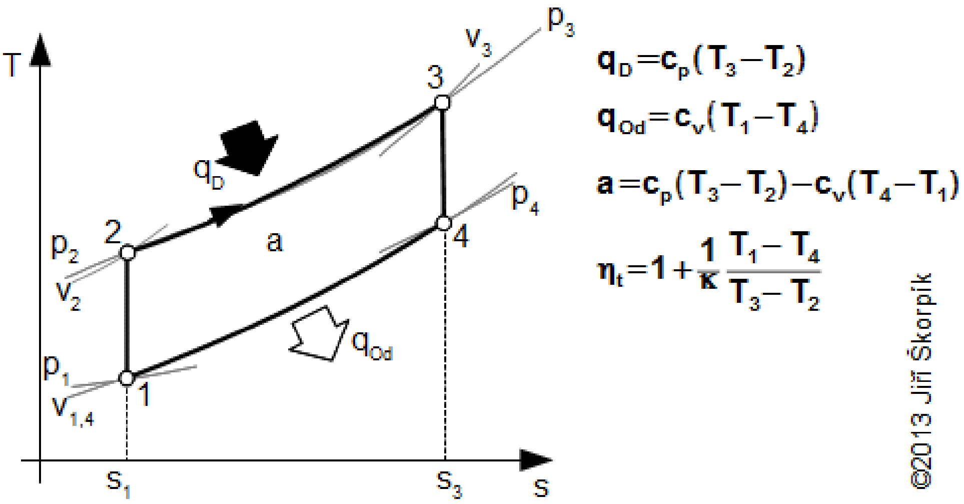
5.978 *p-v diagram of Diesel cycle and its possible realization.*
The ideal realization of the cycle is drawn by the bold line. An approximate real realization of the Diesel cycle is drawn by dashed line.

The suction of air of Diesel cycle proceeds at the motion of the piston to the bottom position and at open suction valve i_v, the state *1*. On the end of the suction is closed the suction valve and the isentropic compression of the air is started from state *1* to state *2*. The pressure ratio is usually about *14* to *23*. The fuel is injected through a nozzle i_p at end of the compression of air. The state *2* of the fuel mix must match a state of self-ignition. Piston move to bottom dead position *3* must taken account a requirements on isobaric combustion. Between states *3-4* is performed isentropic expansion and the piston moves to the bottom dead position. The exhaust valve is opened at the bottom dead position (state *4*), here the bigger portion of mass of the combustion gas is exhausted from the cylinder. The piston is without motion between *1-4*.

The reciprocating motion of the pistons of majority the Diesel engines is transformed on rotary motion through a crank shaft as for case the Otto engines. This mechanism has influence on shape of the cycle and losses.

The two-stroke engine is simpler and has higher power output at the same speed rotation than the four-stroke engine, but it has lower efficiency outside nominal operation condition.

There are more types of the Diesel engines. For example a type with heating plug, which is placed in front of injection of the fuel mix , because for this type of engine must the fuel with air mixes in front of the inlet to the cylinder. If the fuel with low heat of combustion is used (e.g. biogas) then must be use even a spark plug.

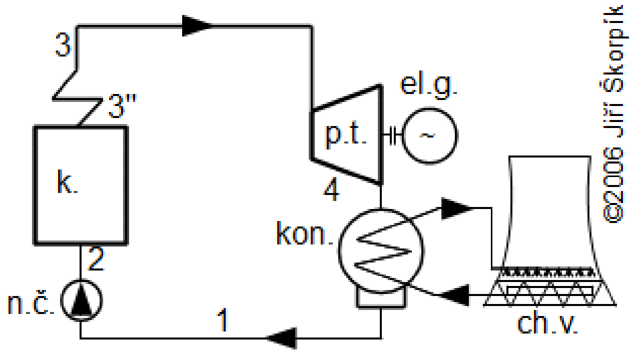


6.979 *T-s diagram of the Diesel cycle and essential equation of its ideal realization.*
For derivation these equations was be used equation of I. law of thermodynamic for closed system, because ideal the Diesel cycle is performed inside cylinder. The derivation of equation for energy balance of the Diesel cycle is shown the Appendix 979.

Inside the Diesel engines is combusted the fuel mix at higher temperature than inside the Otto engines, therefore its internal efficiency is so higher. Disadvantage of high temperature is arise of harmful emissions NOx. The Diesel engine has usually a **supercharging** (an increasing contents of air and fuel inside the cylinder) for increasing of its power output. The supercharging is usually performed by a turbocharger which is powered by the exhaust gas. For the supercharging of engines are used even other ways e.g.: a blower with mechanic drive through shaft of the engine or are used resonance suction tube and etc. The supercharging is usually used at the Diesel engines, because the higher pressure at the suction is not problem. In case the Otto engines, the supercharging need not be always advantage, because the pressure and temperature at the end compression of the fuel mix must lower than is temperature of self-ignition. For this reason is the supercharging used at the Otto engines only for cases: (1) the fuel has lower ignition temperature (e.g. aviation gasoline [2, s. 82]), (2) the density of air is lower (high altitude), for other cases is need decreasing pressure ratio of the engine then the supercharging may not be purposeful.

Rankine-Clausius cycle (R-C cycle; steam cycle)

This cycle is the most widely used worldwide heat cycle in energy industry. The steam cycle is the most old heat cycle which is used in technical praxis and its history is descripted in the chapter 1. History of steam engines. As the working fluid is used water therefore it is colled "steam cycle", but is possible used alternative working fluids [25.]. For transformation heat to work through the steam cycle was used Steam piston engines, but in currently are usually used Steam turbinesteam turbines, but this fact is not change principle of the cycle. The steam turbine is a turbomachine which works continual way and the steam piston engine works discontinual (see chapter 11. Difference between piston engine and turbomachine). The steam cycle is performed through several equipments which are connected by pipes:



7.621 *Simple flow chart of Rankine-Clausius cycle*(6, 7, 8, 9).

k. steam boiler (or steam generator of nuclear power plant; **p.t.** steam turbine or other type of steam engine; **el.g.** electric generator; **kon.** condenser (inside water steam is condensed); **ch.v.** cooling tower; **n.č.** feed pump (it increase pressure of water to boiler).

(6)*Increasing of feed water pressure 1-2*

The increasing of feed water pressure is performed between points *1* and *2* through the feed pump. A power input of the pump is more lower (at comparison with work of the steam turbine at expansion of steam on part *3-4*), because water is almost an incompressible fluid.

(7)*Production of steam from the feed water inside the boiler-steam production*

The steam production can be divided to three step: in the first step *2-3'* is water heated on liquid saturation in the boiler. Other part of the boiler is evaporation of water to the state of steam saturation *3'-3''*. The steam is usually preheated to state *3* in a superheater.

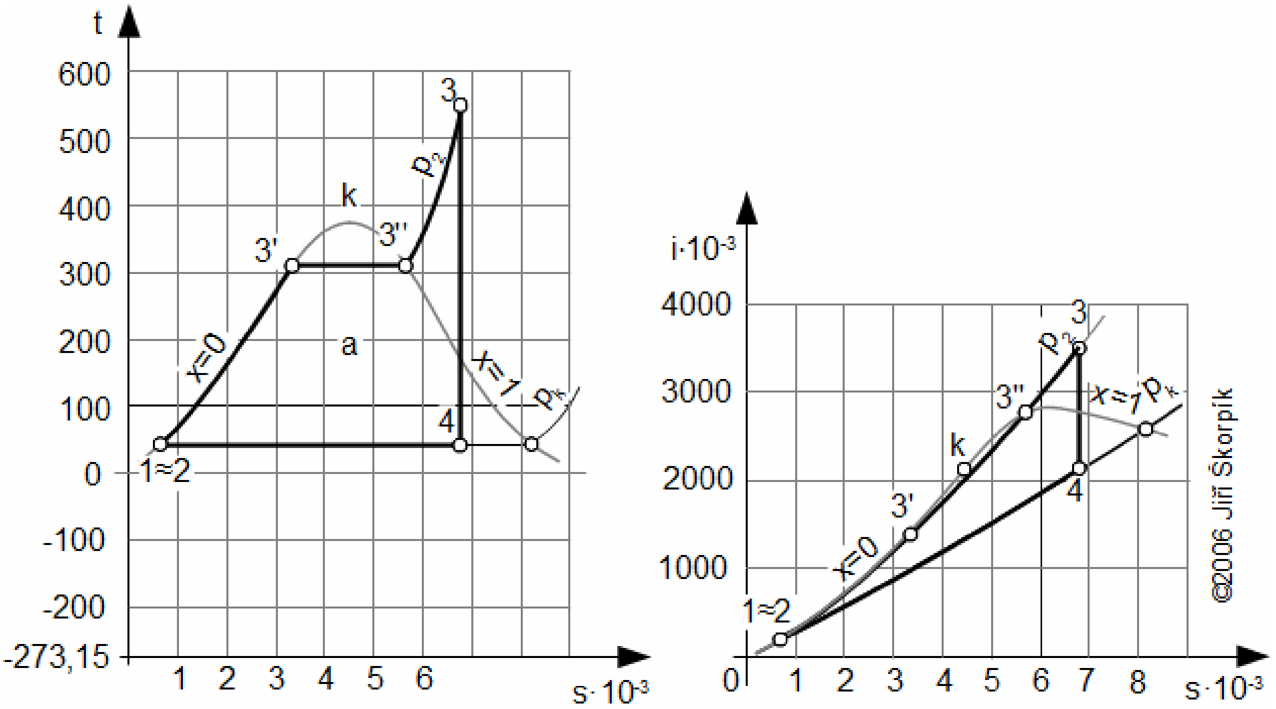
(8)*Expansion of steam in steam turbine*

Inside the turbine is isentropic expansion of the steam from the state *3* to *4*. The work of steam turbine is usually transformed to electricity through an electric generator.

(9)*Condensation of steam inside the condenser*

The condensation of steam is performed inside the condenser after expansion of steam and the steam is condensed from the state *4* (steam) to the state *1* (water). With this step the cycle is closed, because water is again in state *1*. Inside volume of the condenser are placed tubes, in which flows a cooling water for a rejection of condensation heat. The cooling water is cooled example in the cooling towers, but there are other constructions of the condensators and other ways of the its cooling.

The steam cycle which is drawn in T-s or i-s diagram gives real image about a way of transformation energy and energy flows:



8.55 *The steam cycle in T-s and i-s diagram of water and water steam.*
The state of steam in point *3* is *9,4 MPa*, *550 °C*, condensation pressure *9 kPa*. **i** [J·kg^{-1}] specific enthalpy; **t** [°C] temperature; **x** [-] vapor quality (ratio of vapor mass to total mass of volume).

The heat flows to the working fluid is only in the boiler and the heat is rejected is performed only in the condenser. The turbine produces work, and the feed pump consumes work, therefore the work of cycle is a difference of these works:

$$q_D=i_{3c}-i_{2c};\quad q_{0d}=i_{1c}-i_{4c};\quad a=(i_{3c}-i_{2c})+(i_{1c}-i_{4c});\quad \eta_t=1+\frac{i_{1c}-i_{4c}}{i_{3c}-i_{2c}}$$

$$a_T=i_{3c}-i_{4c};\quad a_{\check{c}}=i_{1c}-i_{2c}$$

9.622 *An energy balance of the steam cycle.*
$\mathbf{i_c}$ [J·kg^{-1}] specific stagnation enthalpy; $\mathbf{a_T}$ [J·kg^{-1}] specific internal work of turbine; $\mathbf{a_{\check{c}}}$ [J·kg^{-1}] specific internal work of feed pump. In ideal case individual thermodynamic processes are performed in several equipments, therefore the energy balance is done separately for individual equipment. For derivation equations of energy balance of individual equipment is necessary used equation of First laws of thermodynamic for open system, because the all equipments are open (their input and output) during transformation of energy. These equations are derived for negligible change potential energy of the working fluid. The derivation of the equations for energy balance of the steam cycle are shown in the Appendix 622.

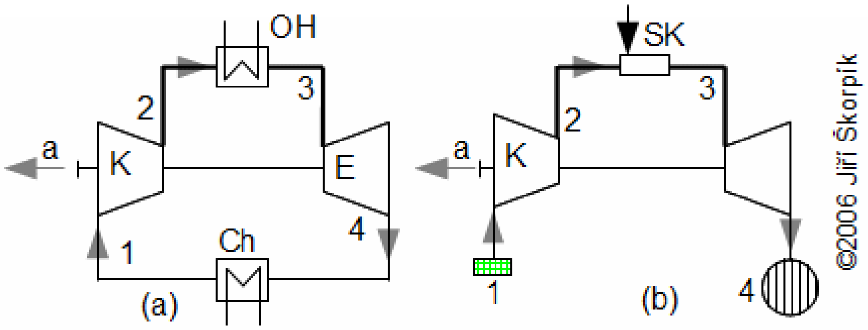
The steam cycle is the cycle with external heat transfer, therefore is possible use wide types of resources of heat (fossil fuels, biomass fuels, solar energy, nuclear energy etc).

Calculate specific work of a turbine, a vapor quality at the exit of the turbine, temperature of water in a condenser, heat efficiency of a steam cycle and compare work of the feed water pump and the turbine for these cycle parameters: temperature of steam at the exit of the boiler *450 °C* at pressure *3,5 MPa*, pressure in the condenser *3 kPa*. Neglect all losses. The solution of this problem is shown in the Appendix 623.
Problem 1.623

A actual flow chart of the steam cycle is not simple, because for higher power output and the efficiency is performed a regeneration of heat, and for heating and other purposes may be performed an extraction steam from several parts of cycle including extractions from the turbine etc. The actual steam cycle is influenced by losses. More information are shown in the article 25. Steam turbine in technological unit.

Brayton cycle (Joule cycle)

Brayton cycle is performed through several equipments. These equipments form a turboset with compression section (turbocompressor) and expansion section (turbine) and as the working fluid is gas. The cycle is usually performed as open cycle (an exchange of the working gas with surroundings), therefore this turboset is called as combustion turbine. The combustion turbines are wide used machines in airplane as a drive jet engine and in power industry. The combustion turbines are wide use machines in airplane as driver jet engine and in power industry.



10.624 *Two examples of flow charts of Brayton cycle.*
(a) closed cycle; **(b)** open cycle (so called the combustion turbines and other types). **K** compression section of turboset; **OH** heater of working gas; **E** expansion section of turboset; **Ch** cooler; **SK** combustion chamber and inlet of fuel.

In individual parts of the turboset are performed these thermodynamic changes in ideal case$^{(10, 11, 12, 13)}$:

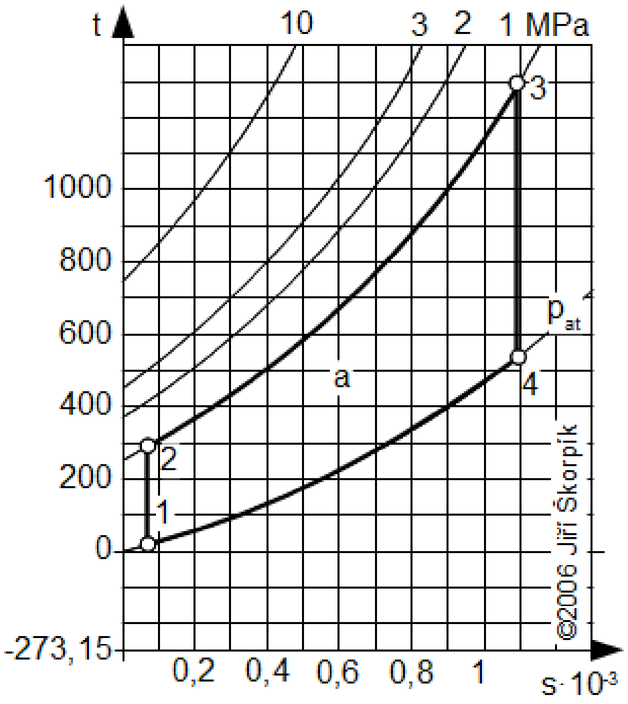
$^{(10)}$*Compression*
The isentropic compression of the working gas from state *1* to state *2* is performed in the compression part.

$^{(11)}$*Heating of gas*
Heating of the working gas from temperature T_2 to temperature T_3 is isobaric process. It is performed inside heater *OH* or the combustion chamber *SK*.

$^{(12)}$*Expansion of gas*
The isentropic expansion of the working from state *3* to state *4* is performed in the turbine section. The working gas does work during expansion, this work is feed rotating shaft. The turbine usually feeds the compressor section through the shaft. The turbocompressor consumes majority portion of work of the turbine. Other portion of work can be used for feed an electric generator.

[13]*Cooling of working gas inside cooler*
The isobaric cooling of the working gas on temperature T_1 is performed inside the cooler. The cycle be can repeated from this state.

The atmospheric air is sucked and compressed to pressure p_2 by the compressor section for case the open cycle. The pressurized air is mixed with fuel (flammable fluid) at pressure p_2 inside the combustion chamber, where it continuously burns. The exhaust gas are rejected to chimney at the end of the expansion.



11.58 *The Brayton cycle in T-s diagram of ideal gas.* Base data sheet of this cycle: c_p*=1,004 J·kg*$^{-1}$*·K*$^{-1}$, (dry air without CO_2 at atmospheric conditions), $\kappa=1{,}402$, $p_1=p_{at}$ (atmospheric pressure), $p_2=1$ *MPa*, $t_1=20$ *°C*, $t_3=1\,300$ *°C*, content of the working gas is stable. For case a combustion turbine is not content of the working gas stable due to burning inside the combustion chamber. This cycle was first performed by Georg Brayton (American) through piston engine.

Energy balance of the Brayton cycle is as follows:

$$q_D=i_{3c}-i_{2c};\quad q_{Od}=i_{1c}-i_{4c};\quad a=(i_{3c}-i_{2c})+(i_{1c}-i_{4c});\quad \eta_t=1+\frac{i_{1c}-i_{4c}}{i_{3c}-i_{2c}}$$

$$a_e=i_{3c}-i_{4c};\quad a_k=i_{1c}-i_{2c}$$

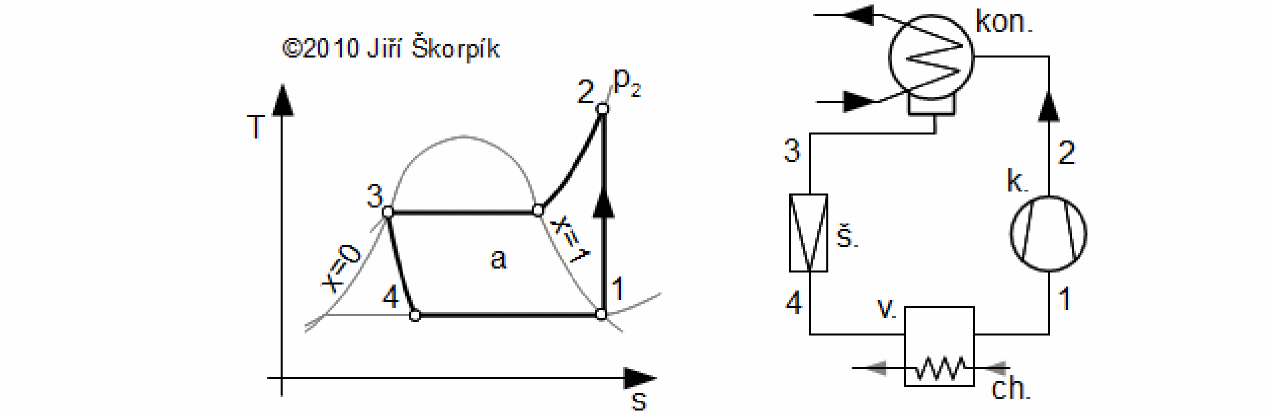
12.59 *Energy balance of the Brayton cycle.*

a$_{\mathbf{e}}$ [J·kg^{-1}] specific internal work at expansion; **a**$_{\mathbf{k}}$ [J·kg^{-1}] specific internal work at compression. The energy balance of individual parts of the gas turbine is done separately. It means that every individual part is solved as a open thermodynamic system. These equations are derived at negligible of potential energy. The derivation of equations for energy balance of the Brayton cycle is shown in Appendix 59.

Calculate temperatures for individual points of a Brayton cycle, its power output, thermal efficiency. Specific heat capacity ratio of a working gas is constant, c_p*=const.=1,004 J·kg*$^{-1}$*·K*$^{-1}$ (dry air at atmospheric condition), $\kappa=1{,}402$, $p_1=p_{at}$, $p_2=1$ *MPa*, $t_1=20$ *°C*, $t_3=1300$ *°C*, $m^\bullet=30$ *kg·s*$^{-1}$. The solution of this problem is shown in the Appendix 625.
Problem 2.625

Vapor-compression refrigeration cycle

There are heat cycles, which transform of work on pressure energy, kinetic energy, potential energy or internal heat energy (e.g. refrigerators, heat pumps and etc.). Especially for case heat pump category is most used Vapor-compression refrigeration cycle. This cycle is similar to the Steam cycle but reverse order of changes of state quantities [3, p. 170], [5]:



13.628 *T-s diagram vapor-compression refrigeration cycle and its flow chart.*
k compressor; **š** expansion valve; **v** **evaporator** (here evaporation of working fluid is carried out); **ch** cooling fluid. Water as the working fluid is not use in this case because it has higher temperature of solidification. The solving water and ammonia is usually used as the working fluid of the vapor-compression refrigeration cycle. Properties of this solving are near to properties of fluid with higher mass ratio in the solving [1, p. 26], [4, p. 508]. T-s diagram of the cycle is function of composition of the solving, but principle of the cycle is the same.

During ideal vapor-compression refrigeration cycle are carried out in the cycle these thermodynamic changes(14, 15, 16, 17):

(14)*Compression of working gas*
The compression from state *1* to state *2* is performed by the compressor.

(15)*Cooling and condensation of working gas*
The working gas is cooled on saturation in first step and then it is condensed to saturation of liquid state *3* at pressure p_2 inside the condenser.

(16)*Throttling of saturation liquid*
The throttling of saturation liquid is performed by the expansion valve (decreasing of pressure from p_2 on p_3). Portion of working liquid is vaporized during throttling, therefore at the end the expansion valve there is the working fluid in state wet steam.

(17)*Evaporation of working liquid*
The evaporation of the working liquid is performed in the evaporator at the exit is the working gas in state saturation steam *1*.

Heat is delivery to the cycle through the evaporator and is rejected through the condenser. This type of cycle consumes work through compression:

$$q_D=i_{1c}-i_{c4}\ ;\ \ q_{Od}=i_{3c}-i_{2c}\ ;\ \ a=i_{1c}-i_{2c}=a_k$$

$$\varepsilon_R=\frac{q_{Od}}{a}$$

14.629 *Equations of energy balance of the vapor-compressor refrigeration cycle.*
ε_R [-] **coefficient of performance**(18). The work of the cycle is negative. The individual parts of the cycle are open thermodynamic systems. The equations are derived at negligible of change of kinetic energy. The derivation of the equations of energy balance of the refrigeration cycle is shown in Appendix 629.

(18)Coefficient of performance
From definition of the coefficient of performance is evident, the compression work is increased with decreasing difference of temperature between of surroundings and the cooling fluid.

The refrigeration cycles are used for cooling or heating as heat pump. For case the cooling heat is taken from cool substance through an evaporator, which is usually located inside volume of cool substance or inside flow of cool substance.

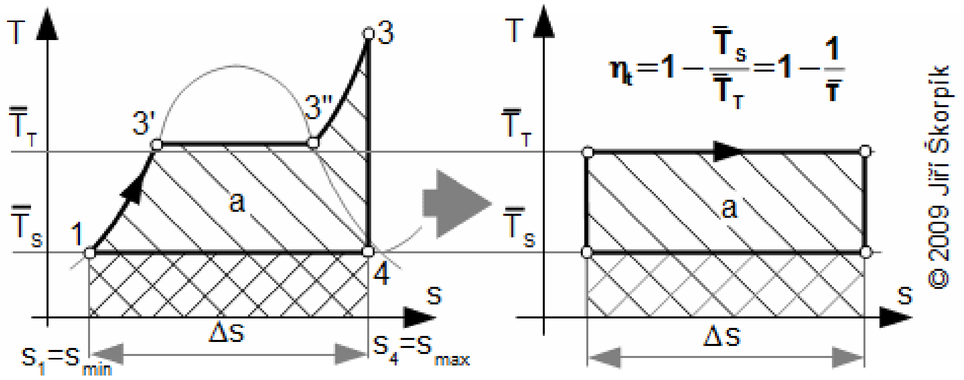
Carnotization of heat cycle

For all types of cycles can be defined **mean temperature of input heat of cycle $\bar{T}_T$** and **mean temperature of rejection heat of cycle $\bar{T}_S$**:

$$\bar{T}_T=\frac{\int_{s_{min}}^{s_{max}} T\cdot ds}{s_{max}-s_{min}}\ ;\ \ \bar{T}_S=\frac{\int_{s_{max}}^{s_{min}} T\cdot ds}{s_{max}-s_{min}}$$

15.172 *The mean temperature of input heat and rejection heat of heat cycle.*
$\bar{T}_T$ [K] mean temperature of input heat of cycle; **$\bar{T}_S$** [K] mean temperature of rejection heat of cycle. The mean temperature of input heat of cycle is equivalent of temperature at isothermal process between entropies s_{min} and s_{max} of solved heat cycle, where the amount input of heat at this isothermal process is the same as amount of input heat of solved heat cycle on this part of the cycle. The mean temperature of rejection heat of cycle is equivalent of temperature at isothermal process between entropies s_{max} and s_{min} of solved heat cycle, where the amount rejection of heat at this isothermal process is the same as amount of rejection heat of solved heat cycle on this part of the cycle.

For example, for case the Carnot cycle is mean temperature of input heat of cycle equivalent to temperature T_1 ($\bar{T}_T=T_1$) and mean temperature of rejection heat of cycle equivalent to temperature T_3 ($\bar{T}_S=T_3$). At steam cycle are temperatures $\bar{T}_T$ and $\bar{T}_S$ is as follows:



16.125 *The steam cycle – definition of mean temperature of input heat and rejection heat of cycle.*
$\bar{\tau}$ [-] temperature ratio of mean temperatures. The mean temperature of input heat of cycle is located between temperatures T_2 and T_3. The mean temperature of rejection heat of cycle is equivalent to condensation temperature T_1, because heat leaves the cycle only at condensation respective at isothermal process. A cycle which is composed of mean temperatures ($\bar{T}_T$; $\bar{T}_S$) and with equivalent difference entropy is equivalent a Carnot cycle with same work and input heat and rejection heat. This cycle must be same efficiency as examinee steam cycle.

Purpose this comparison is recovered possibilities of higher thermal efficiency cycles. The thermal efficiency is increasing with higher temperature ratio $\bar{\tau}$. It means that through increase the mean temperature of input heat or through decrease the mean temperature of rejection heat. For example, for case the steam cycle is evident that increasing pressure p_2 is way to higher the mean temperature of input heat of cycle even to higher thermal efficiency regardless maximum temperature of the cycle. Similar way be can defined temperatures $\bar{T}_T$ and $\bar{T}_S$ for any heat cycle and through these temperatures is can assessed influence individual parameter of the working fluid on thermal efficiency. Process comparing a heat cycle with the Carnot cycle with purpose higher thermal efficiency is called **Carnotization**. For example, in energy industry is used Carnotization of steam cycle and Carnotization of Brayton cycle etc.

From compare the heat cycles with Carnot cycle is evident that for efficiency is most significant the temperature ratio $\bar{\tau}$ and not temperature ratio between maximum and minimum temperature of cycles.

Heat machines and similar terms

By heat machine is called machine in which runs transformation internal energy and usually pressure energy of the working fluid on work or opposite(19, 20). It means heat exchangers (boilers, condensators and burners) are not the heat machines.

(19)Thermal power plant

Through this term is called complex of buildings and accessories for purpose of production of electricity through a heat cycle. According primary fuel or its principle are used also the terms as e.g. fossil power plant, geothermal power plant, nuclear power plant, solar power plant... Efficiency of heat transformation to electric power through the thermal power plant is called **efficiency of thermal power plant** (also thermal efficiency), it is defined as a ratio between the electric power output on border of the power plant and an energy useable flow in fuel which entered to the power plant:

$$\eta=\frac{P_E}{P_{pal}}$$

17.1091 *Efficiency of thermal power plant.*

η [-] efficiency of thermal power plant; **P_e** [W] electric power output of unit on border of the power plant; **P_{pal}** [W] energy useable flow in fuel entred to power plant.

(20)Combined heat and power plant

Through this term is usually called a complex of buildings and accessories for purpose of production of electricity and heat energy through some heat cycle (this process is called **combined heat and power** (**CHP**) or **cogeneration**). The portion of heat must be rejected during transformation heat on work. This rejection heat can be use for heating (if near there is the heating consumer then it is can feed through a caliduct or a steam piping). The use of the rejection heat increase efficiency use energy in fuel. The CHP units must produce of heat in case a disorder on technology part for production electricity, because primary function of CHP units is production of heat. Temperature of working fluid in the caliduct and steam pipes must be on required levels (e.g. for heating and hot water for domestic *80 °C* up *90 °C*, for industry use higher), but an increasing mean temperature of rejection heat of heat cycle causes a decrease thermal efficiency of the cycle. For case the Power and heating plant to *2 MW* power output is usually used term a **Cogeneration unit**. Characteristic parameters of CHP are a **power to heat ratio** and a cogeneration efficiency:

$$\eta^{tep}=\frac{P_e+P_T}{P_{pal}};\ e=\frac{P_e}{P_T}$$

18.479 *A cogeneration efficiency and a power to heat ratio.*

η^{tep} [-] cogeneration efficiency of unit; **e** [-] power to heat ratio. **P_T** [W] heat power output of unit; .

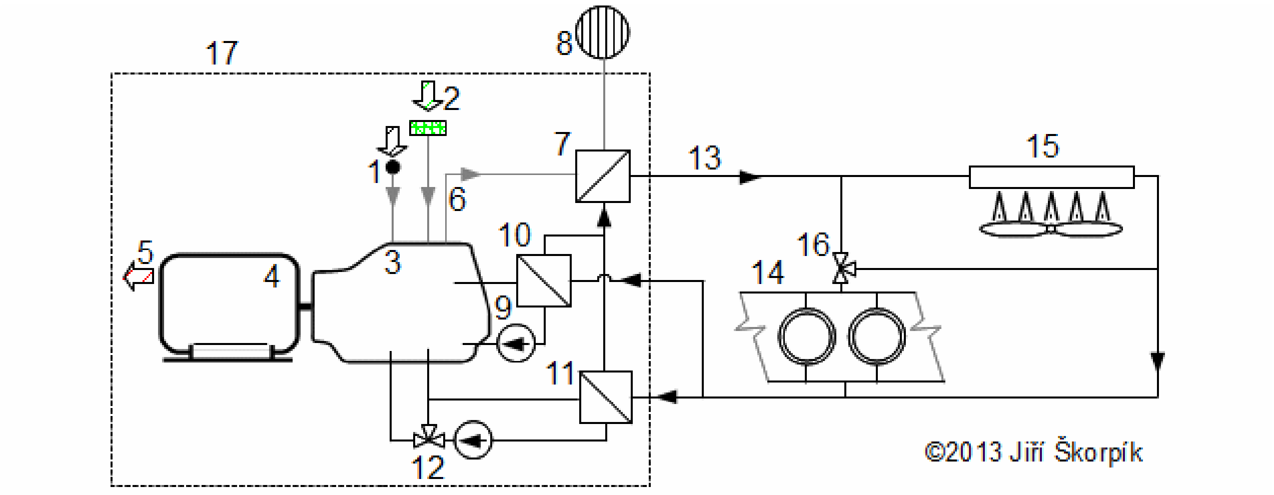
The power to heat ratio of CHP unit is function of type of heat machine and its power:

Type of CHP unit	e [-]
with steam cycle	0,15..0,4
with Brayton cycle	0,4...0,7
with internal combustion engines*	0,6...0,8
with combined cycle gas turbine	0,7...1,2

19.967 *The power to heat ratio according type of CHP unit.*

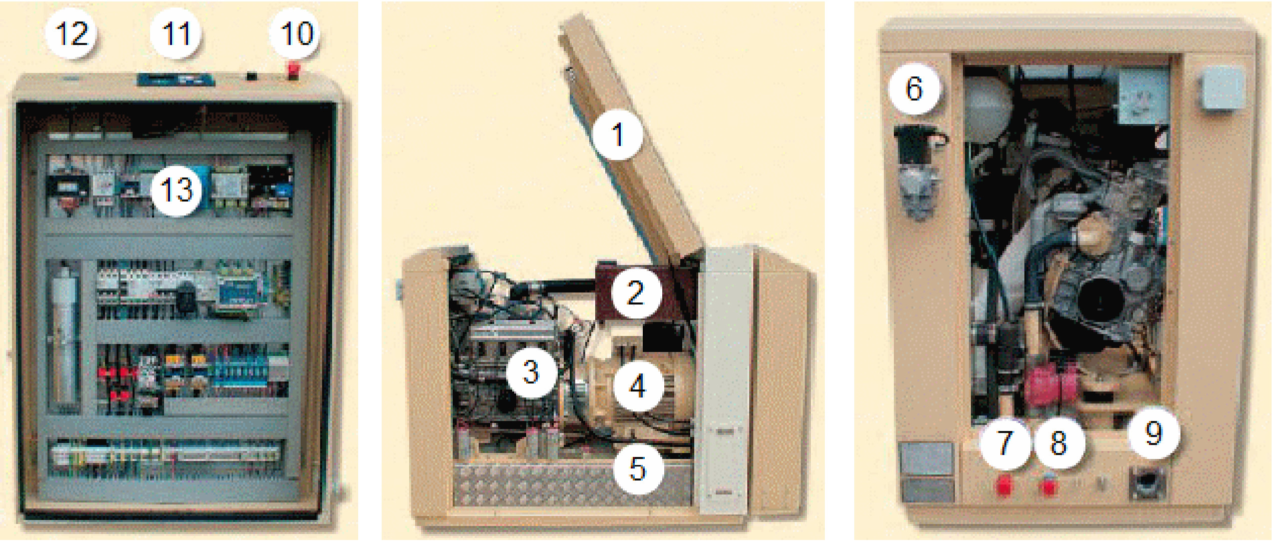
*Only at higher power output. The power to heat ratios other types of CHP units are shown chapter 10. Cogeneration in households.

The most use types of CHP unit in Czech republic are CHP units with internal combustion engines, CHP units with steam turbines and CHP units with combustion turbines. The CHP unit must contain an outlet of electric power even an outlet of heat for a heat consumers:



20.208 *Flow chart of CHP unit with internal combustion engine.*
1 fuel input; **2** inlet of combustion air through filter; **3** internal combustion engine; **4** electric generator; **5** electricity line; **6** exhaust of hot gas outside engine; **7** heat exchanger exhaust gas/water (instead this exchanger can be an steam generator); **8** chimney; **9** loop of cooling water of engine with circulating pump; **10** heat exchanger cooling water/water; **11** heat exchanger oil/water; **12** regulation of flow and temperature oil; **13** hot water from cogeneration unit; **14** consumer of hot water; **15** cooler (if consumers **14** has decreasing power output or they off); ; **16** regulation of temperature and mass flow rate of hot water for consumers; **17** boundary of cogeneration unit.

Small cogeneration unit with combustion engine are delivered in compact pack, but for cases bigger units is necessary building a machine room and an infrastructure:



21.209 *A cogeneration unit with combustion engine about 20 kW power output.*
1 acoustic cover; **2** oil tank; **3** combustion engine; **4** generator; **5** heat exchanger of exhaust gas and silencer of noise; **6** inlet of fuel gas; **7** exit of heating water; **8** input of heating water; **9** exhaust; **10** main switch; **11** control system; **12** counter of time of operation; **13** switchboard. The figures are not to scale. On base [6].

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