CYCLES OF POWER PLANTS

THERMODYNAMICS

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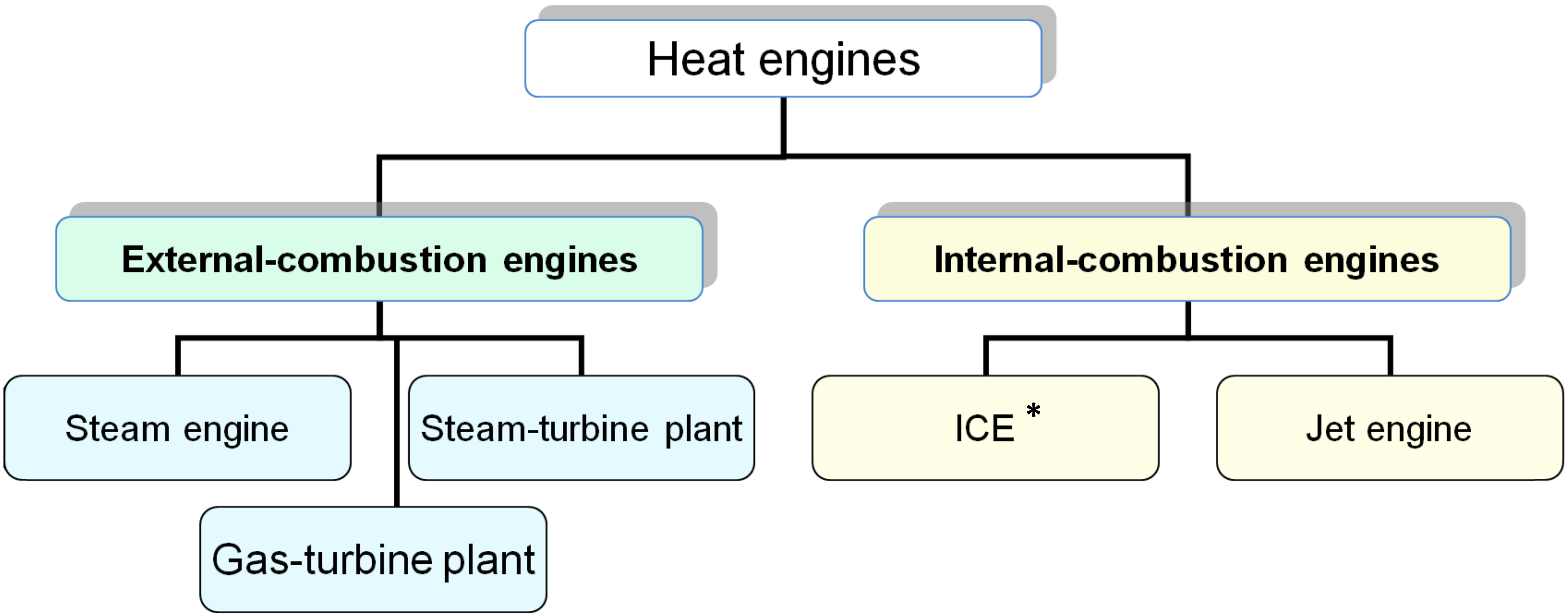
Definitions

- **Power plant** is a complex of interrelated equipment and constructions serving to convert, transfer, accumulate and distribute/consume energy

- **Heat engines** are power plants designed to convert heat into mechanical work

Types of heat engines



* **ICE** – Internal Combustion Engine

Processes in heat engines

Thermodynamic cycles corresponding to the various engines

Heating and cooling processes

Isobaric
$\Delta P = 0$

Isochoric
$\Delta V = 0$

Isothermal
$\Delta T = 0$

Compression and expansion processes

Isentropic
$\Delta S = 0$

Brayton cycle

Standard Otto cycle

Carnot cycle

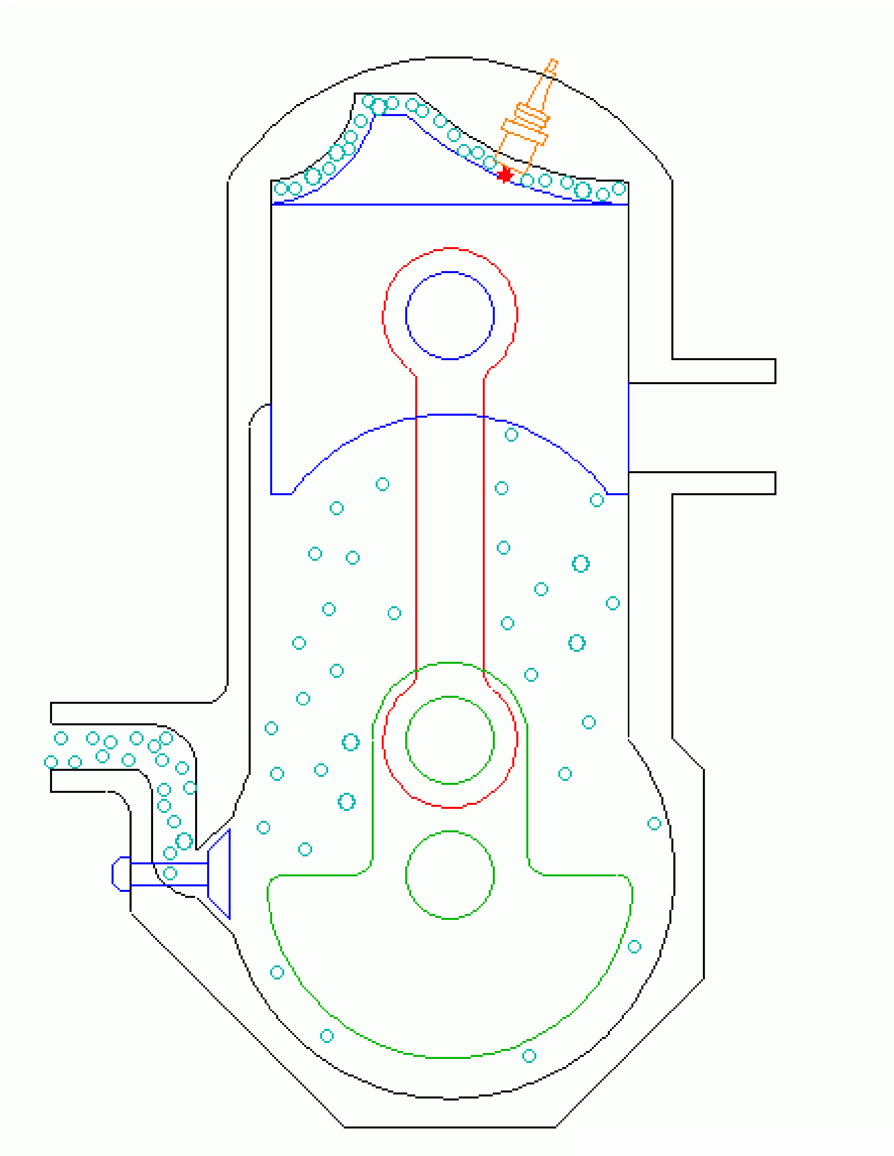
Standard Diesel cycle
(heating) *(cooling)*

Isothermal
$\Delta T = 0$

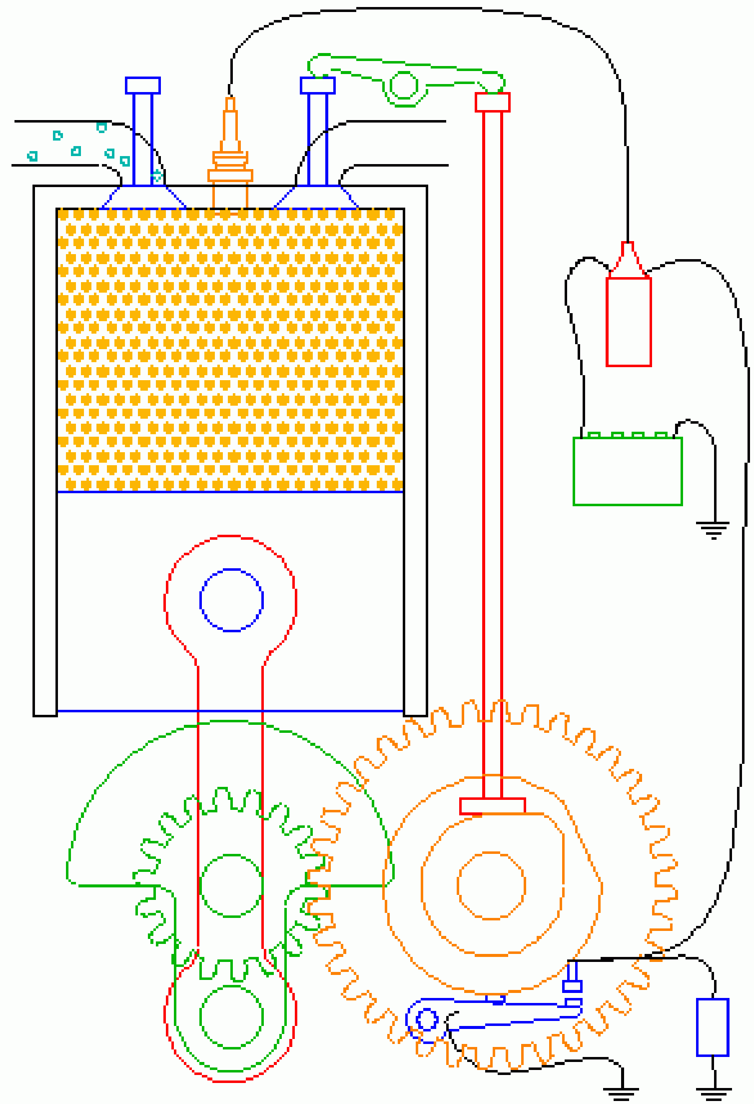
Ericsson cycle

Stirling cycle

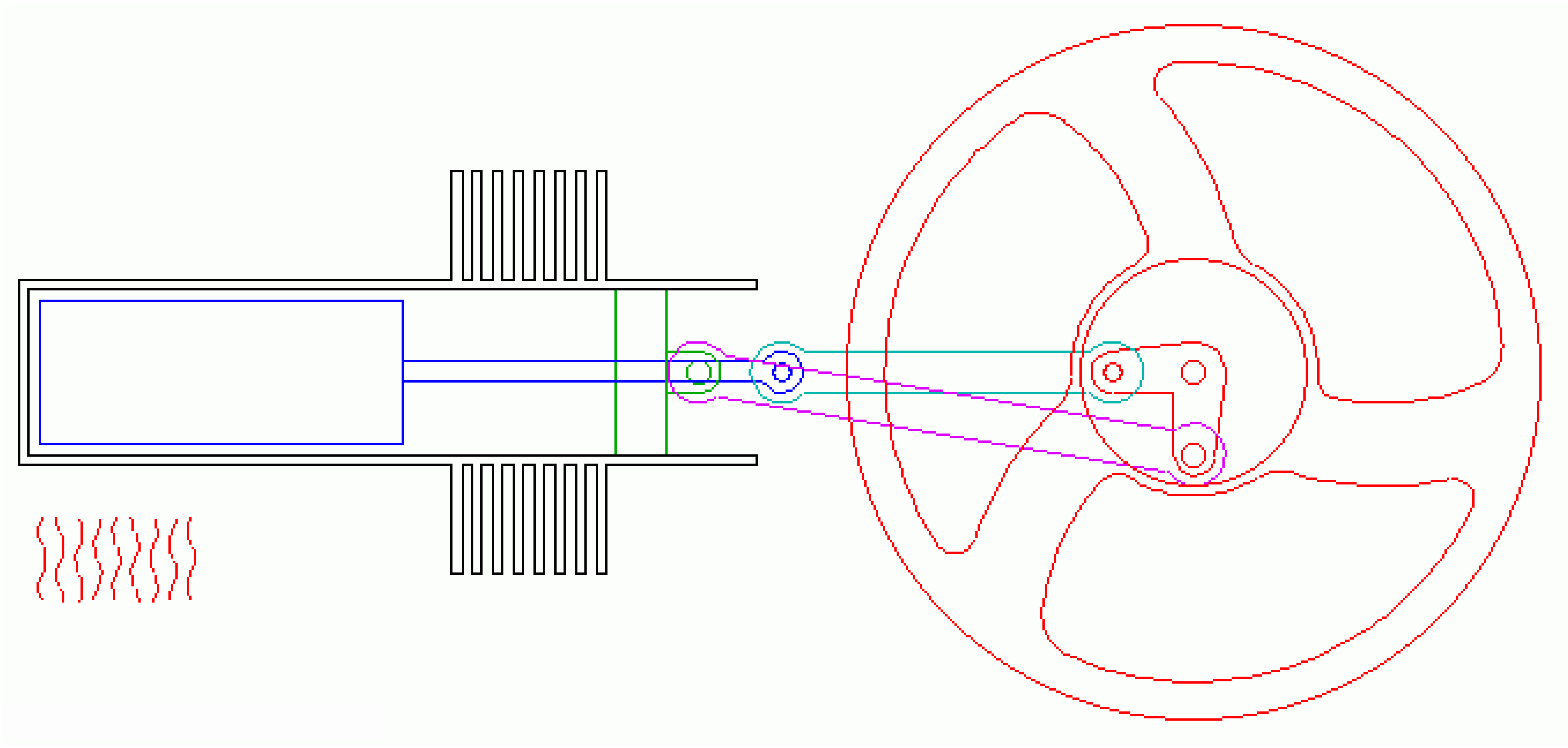
Internal combustion two-stroke engine



Otto four-stroke engine



Stirling engine

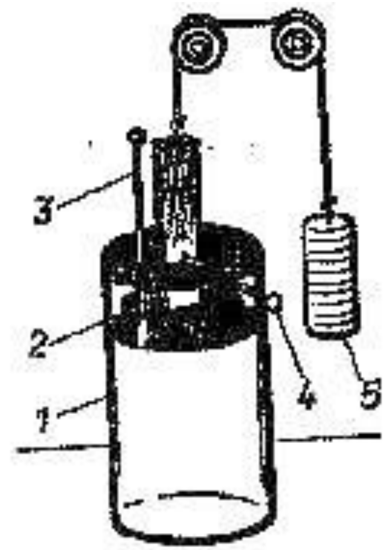


Examples of steam engines

- Boiler designed by Denis Papin (in 1690)

1 – cylinder, 2 – piston, 3 – joint-pin,

4 – linchpin, 5 – load

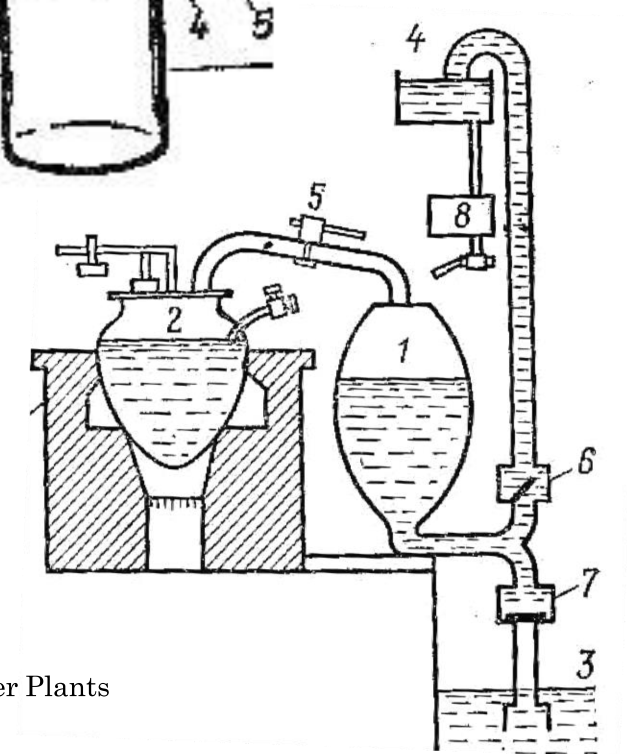


- Pistonless water lift designed by Thomas Savery (in 1698)

1 – container, 2 – boiler,

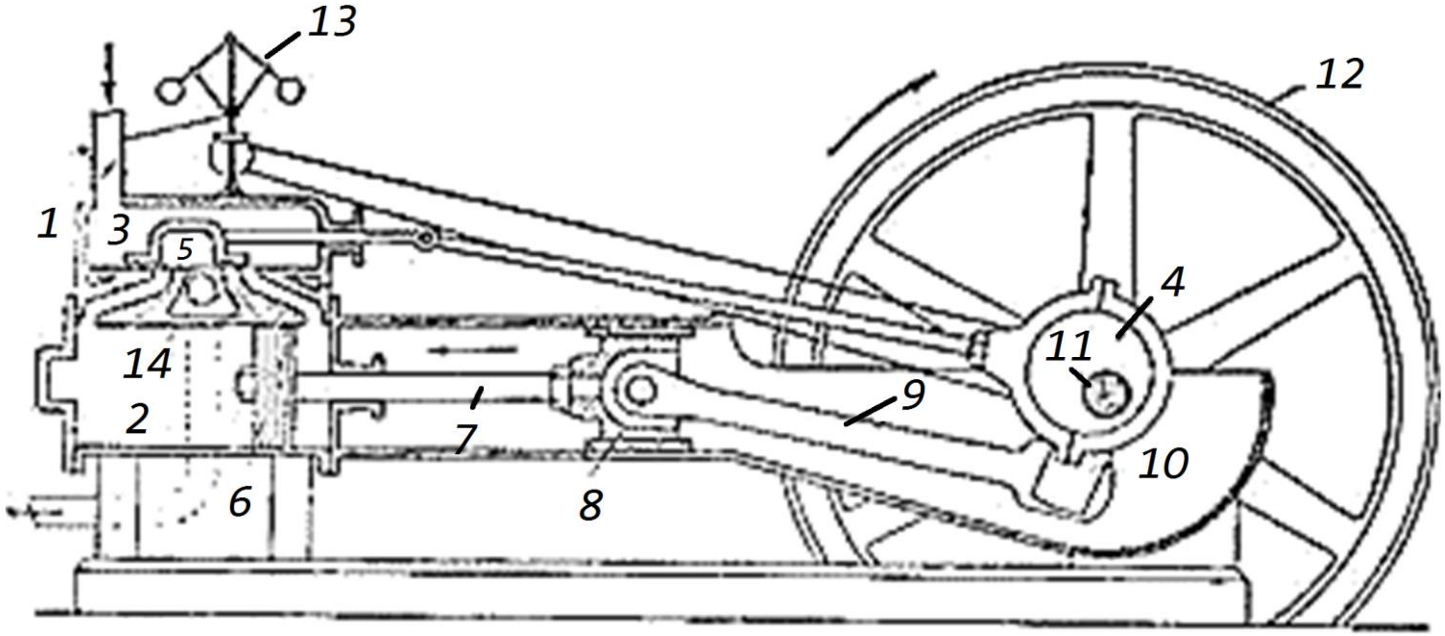
3 – water reservoir, 4 – tank,

5 – tap, 6 and 7 – valves, 8 – tank



Steam engines

Universal steam engine designed by James Watt in 1784



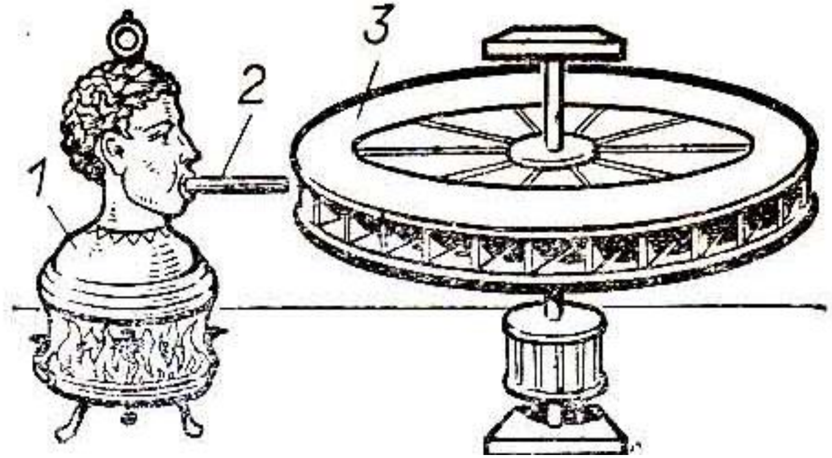
*1 – slide box, 2 – cylinder, 3 – piston valve, 4 – eccentric,
5 – viewing window, 6 – piston, 7 – rod, 8 – slider, 9 – conrod, 10 – crank,
11 – shaft, 12 – flywheel, 13 – speed control, 14 – exhaust pipe*

Steam turbines

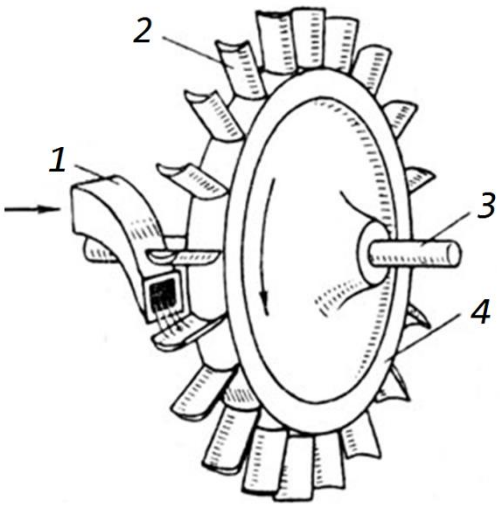
Turbine of Giovanni Branca (XVII century)

1 – boiler, 2 – nozzle,

3 – paddles of the wheel



Scheme of conversion of heat energy into mechanical energy in turbine



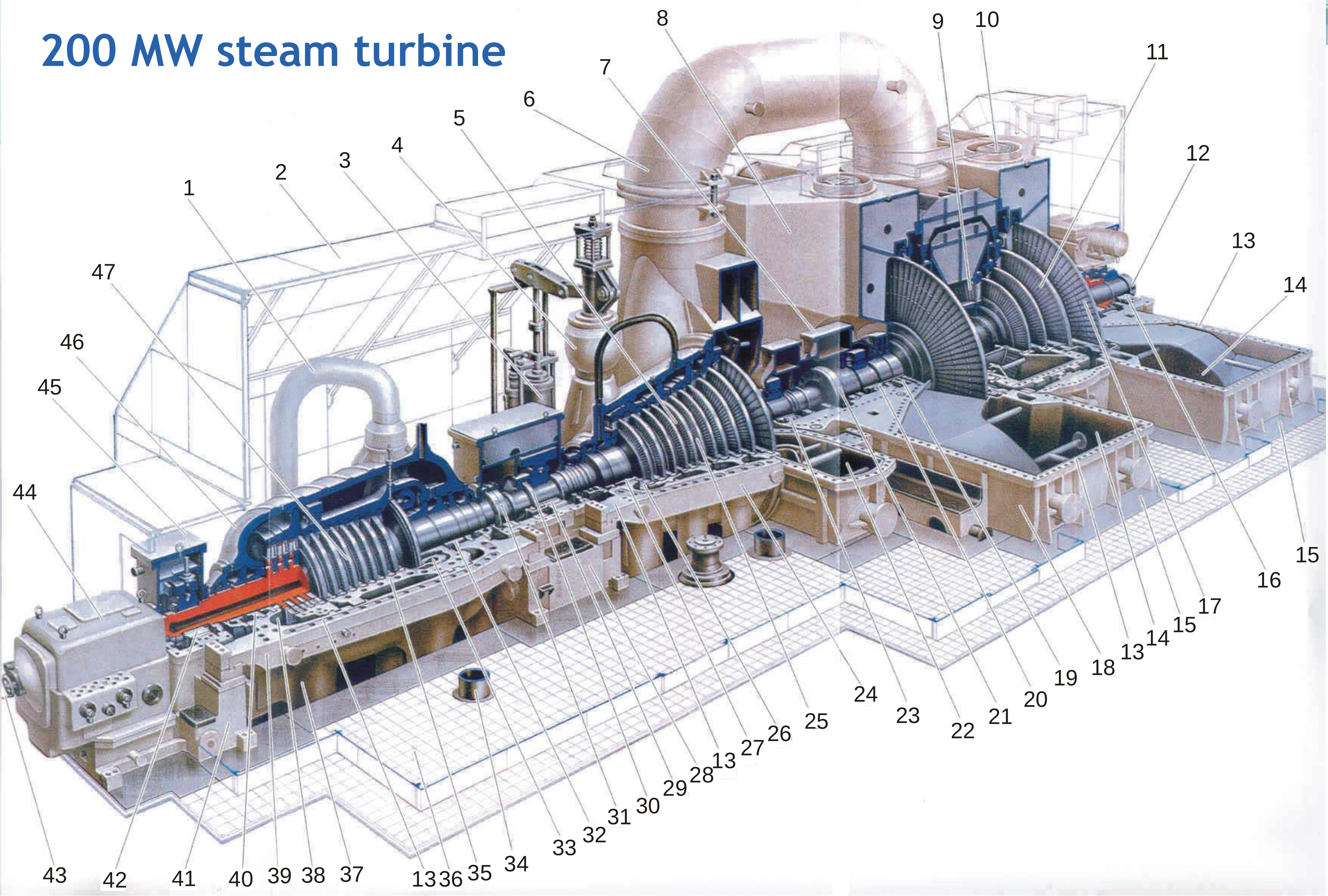
1 – nozzle

2 – paddles of the wheel

3 – rotor

4 – wheel

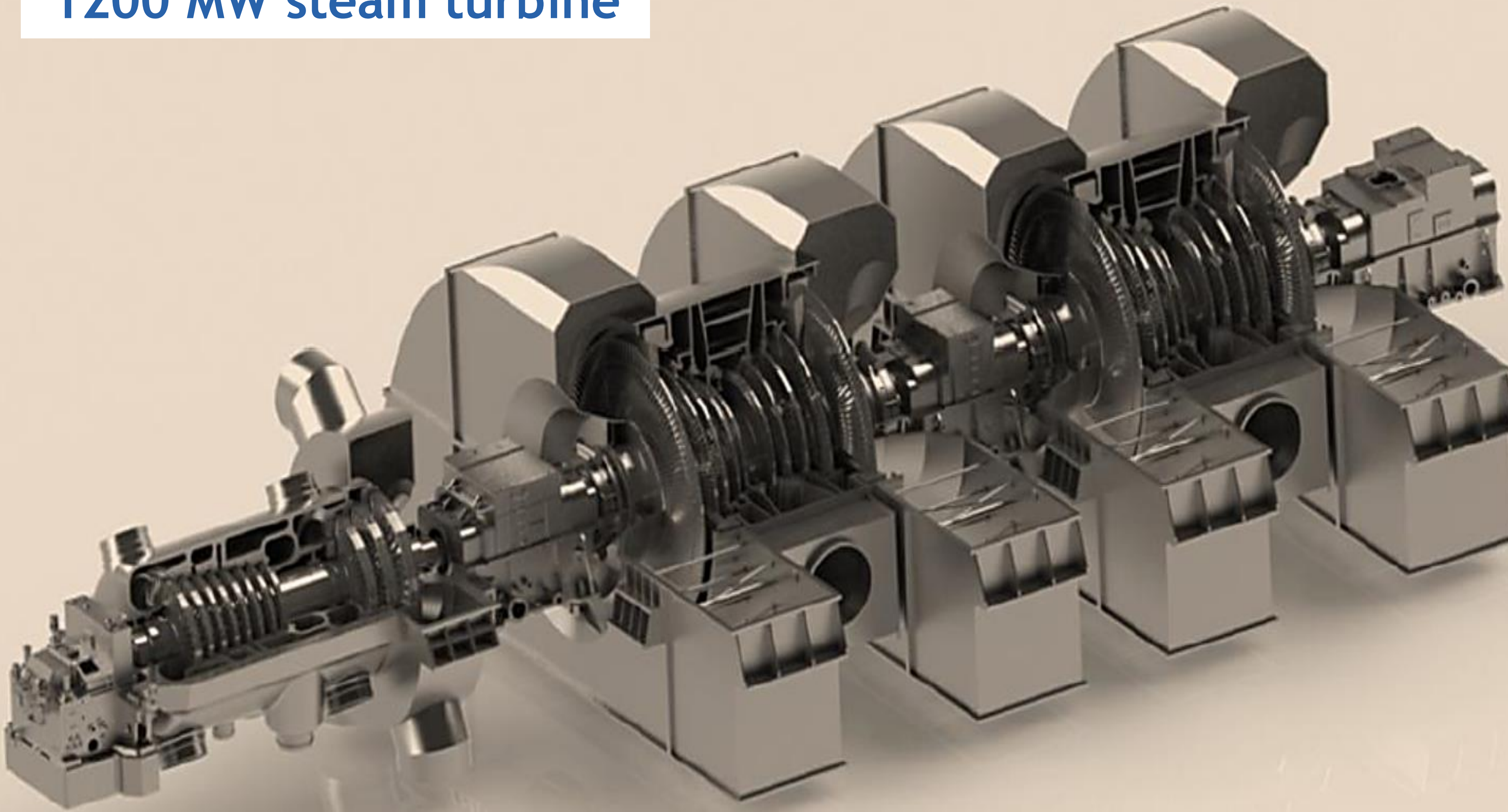
200 MW steam turbine



Design of a typical steam turbine

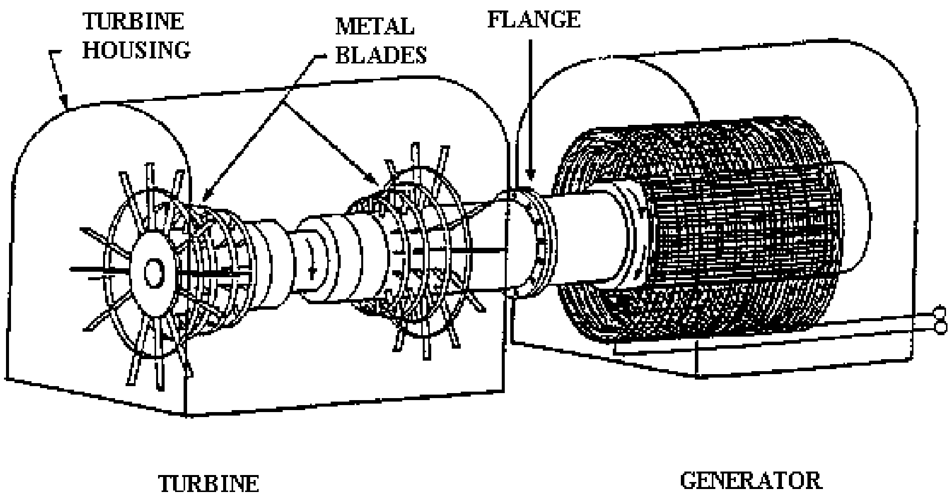
1 – pipe to supply steam to HPC; 2 – housing; 3 – servo motor of the MPC control valve; 4 – MPC control valve; 5 – MPC rotor; 6 – receiver tube to bypass steam from MPC to LPC; 7 – LPC rotor support; 8 – upper half of the LPC shell; 10 – dump steam atmospheric valve, opens in case of overpressure in the LPC exhaust pipe; 11 – LPC rotor; 12 – half-coupling to connect to the power generator rotor; 13 – surfaces of the horizontal joint of cylinder shells; 14 – LPC exit nozzle, from which steam enters the condenser located under the turbine; 15 – LPC supporting skirt; 16 – LPC back shaft bearing; 17 – working blades of the last stage of LPC; 18 – lower half of the LPC shell; 19 – rear end seal of LPC; 20 – LPC front bearing; 21 – coupling to connect MPC and LPC rotors; 22 – MPC exit nozzle; 23 –MPC back shaft bearing; 24 – lower half of the MPC shell; 25 – MPC working blades; 26 – MPC steam supply chamber; 27–28 – lower half of the intermediate shaft support; 29 – support pad of the intermediate bearing; 30 – thrust collar; 31 – coupling to connect HPC and MPC rotors; 32 – rear end seal of HPC; 33 – steam supply chamber for live steam; 34 – steam line to supply steam to HPC (similar to 1); 35 – inner HPC shell; 36 – upper ground plate; 37 – exit nozzle of HPC to extract steam for reheating; 38 – HPC outlet chamber; 39 – lower half of the HPC shell; 40 – front end seal of HPC; 41 – lower half of the housing of the front HPC support; 42 –HPC front shaft bearing; 43 – turbine control mechanism; 44 – turbine control and regulation unit; 45 – front support; 46 – upper half of the outer HPC shell; 47 – HPC rotor

1200 MW steam turbine



Cycles of power plants

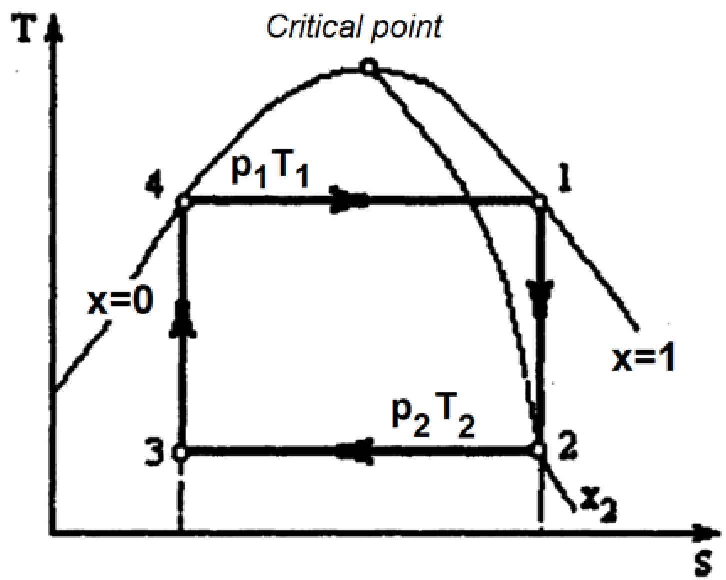
Turbine *is a* a rotary mechanical device which converts the heat energy of working medium (*steam* or *gas*) into the kinetic energy and then into rotational energy of the rotor of a turbine. The turbine rotates the rotor of the generator.



In power engineering steam turbine and gas turbine cycles are used the most widely. In these cycles turbines are used as engines

Carnot water steam cycle

The most efficient heat engine cycle is the **Carnot cycle**.



Carnot cycle in Ts-diagram

Carnot cycle with water steam working fluid

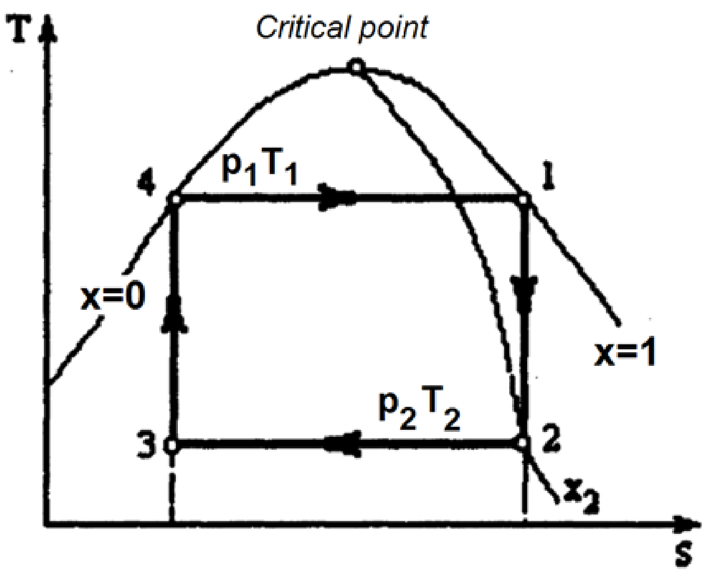
1-2 – isentropic expansion

2-3 – simultaneously isothermal and isobaric heat removal

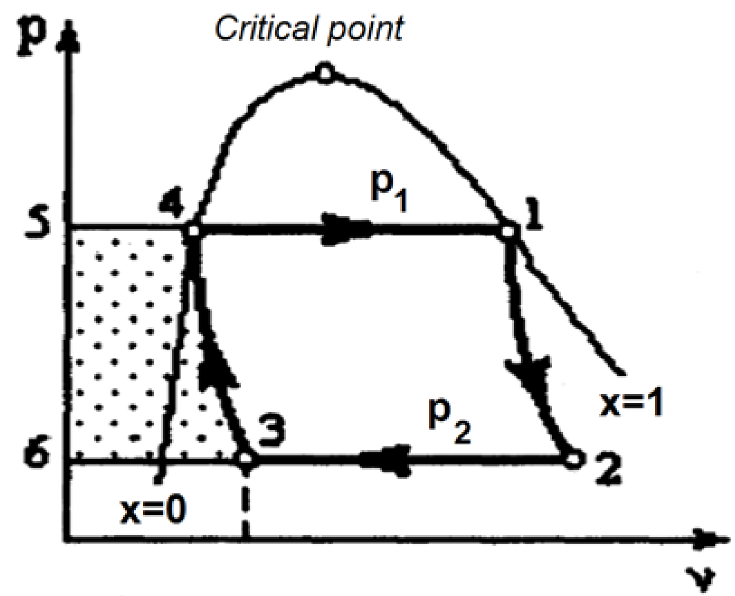
3-4 – isentropic compression

4-1 – simultaneously isothermal and isobaric heat supply

Carnot water steam cycle



Carnot cycle in Ts-diagram



Carnot cycle in pv-diagram

States of the working medium:

- (1) dry saturated steam at pressure p_1 $(x = 1)$
- (2, 3) wet steam at pressure p_2 $(x_3 \ll x_2)$
- (4) boiling water at pressure p_1

Features of the Carnot cycle with water steam

1) Temperature in process of heat supply is limited to the temperature of the *critical point* $(t_{cr} = 374.15\ ℃)$, i.e. maximum temperature at the turbine inlet is $t_1 = 350\ ℃$.

2) Temperature of the cold source is limited by the conditions of heat exchange with the environment. Its value is $t_2 = 25\ ℃$ and greater.

3) Maximum value of thermal efficiency for these temperatures is equal to:

$$\boxed{\eta_t = 1 - \frac{T_2}{T_1} = 1 - \frac{25 + 273}{350 + 273} = 0.522}$$

Features of the Carnot water steam cycle

4) Gas expansion in the turbine at the above parameters ends in the zone of high humidity (41%), which is unacceptable in practice because of erosive wear of components and units of the turbine. The maximum humidity value is 12 – 14 %.

5) Compression of the saturated gas in a compressor occurs in more severe conditions: humidity value of the steam increases up to 100%. *There are no engines which would operate at this humidity value.*

Exergy efficiency of the Carnot cycle

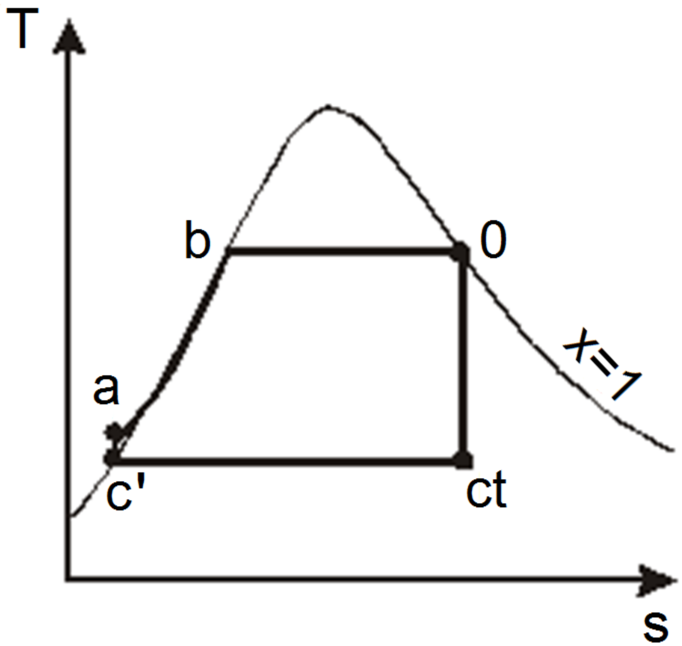
Exergy efficiency reflects objectively energy dependence of any device since the Rankine cycle is the most efficient cycle of the heat engine, so:

$$\boxed{\eta = \frac{(T_1 - T_2) \cdot (s_4 - s_1)}{T_1 \cdot (s_4 - s_1) \cdot \dfrac{(T_1 - T_2)}{T_1}} = 1}$$

Rankine cycle

A Scottish mechanical engineer William John Rankine suggested replacing differential condensation of steam in the process of heat removal with complete condensation. Therefore, during compression a working medium is in a liquid state, and a pump is used instead of a compressor.

Rankine cycle with saturated steam



Rankine cycle with saturated steam in Ts-diagram

0-ct – isentropic expansion of the steam in a turbine

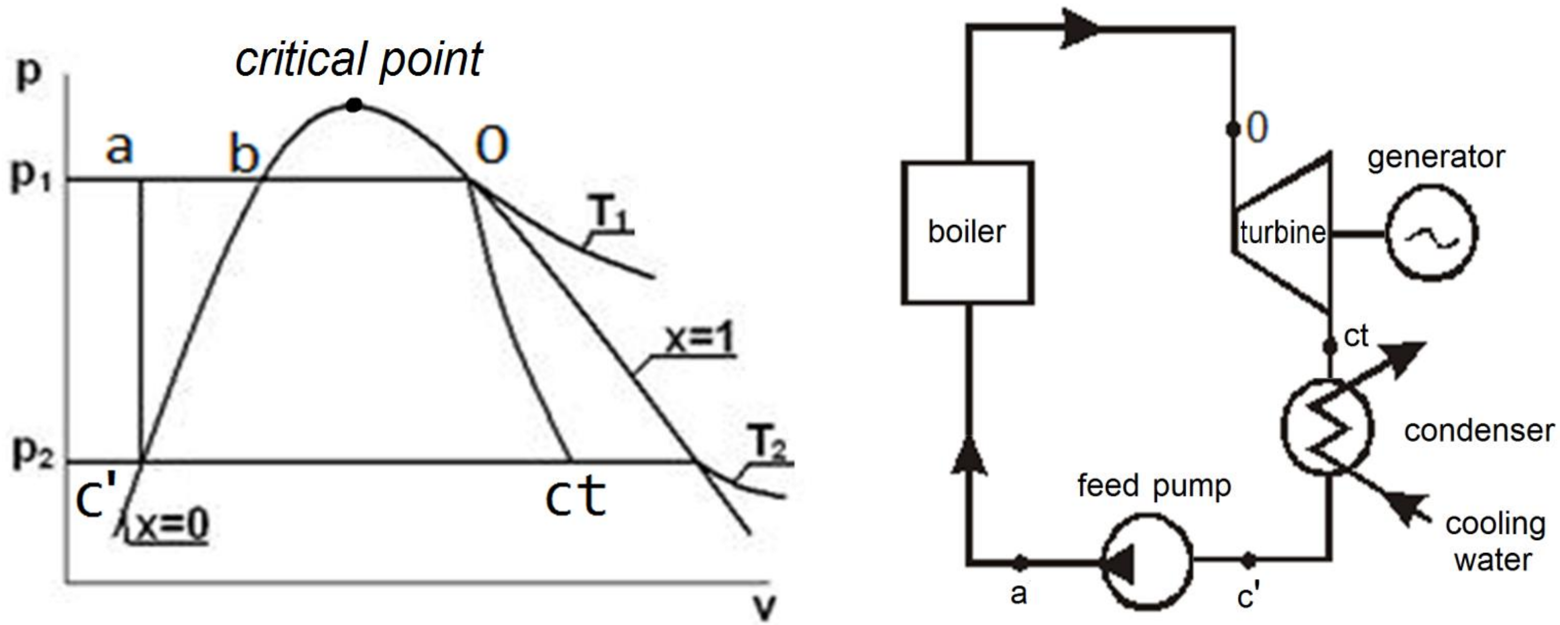
ct-c' – isobaric heat removal in a condenser, steam returns to liquid

c'-a – isentropic compression of a liquid in a pump

a-b – heating water to a boiling point at $p_0 = const$

b-0 – boiling water generates steam at $p_0 = const$ and $T_0 = const$

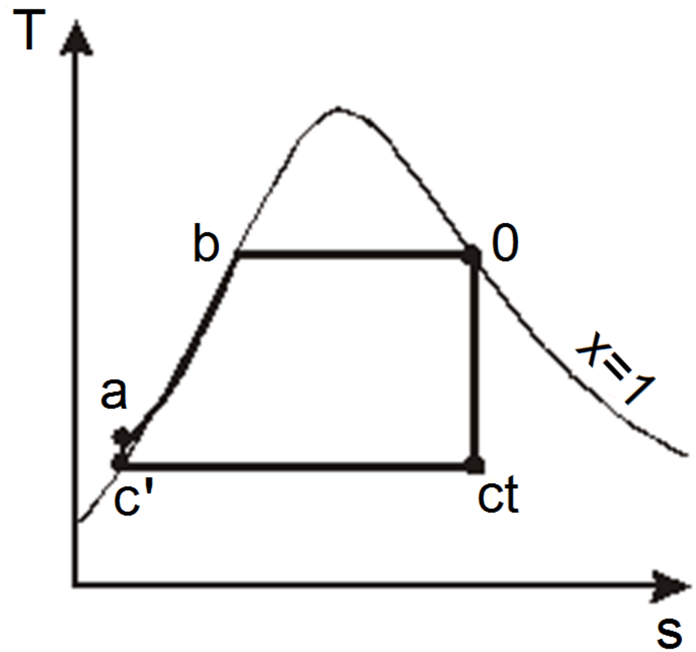
Rankine cycle with saturated steam



Rankine cycle with saturated steam

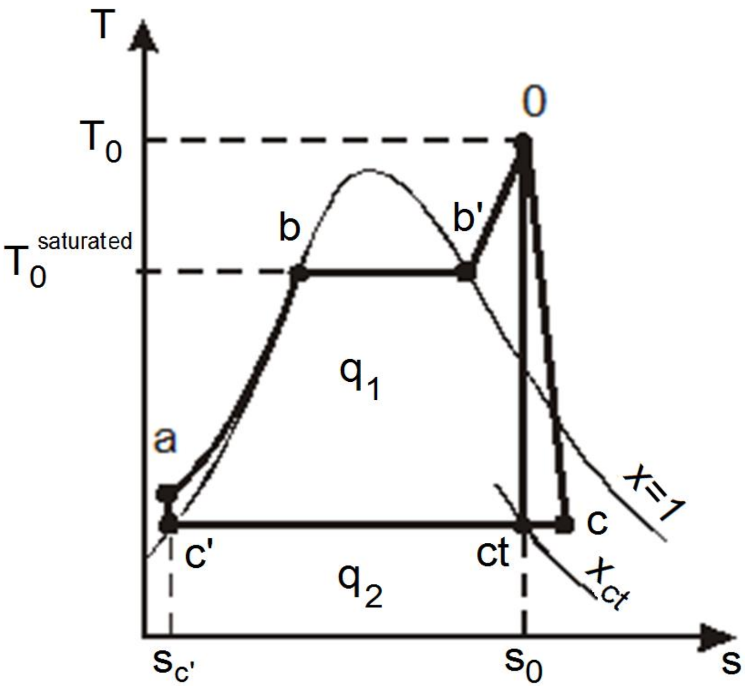
Disadvantage of this cycle is a *high moisture content* at the outlet of the turbine like in a Carnot cycle. Consequently, this cycle is suitable only for low initial pressure of steam ($p_0 \leq 0{,}5\ MPa$).

Thermal efficiency of Rankine cycle with saturated steam



$$\eta_t = \frac{(h_0 - h_{ct}) - (h_a - h_{c'})}{h_0 - h_a}$$

Rankine cycle with reheated steam



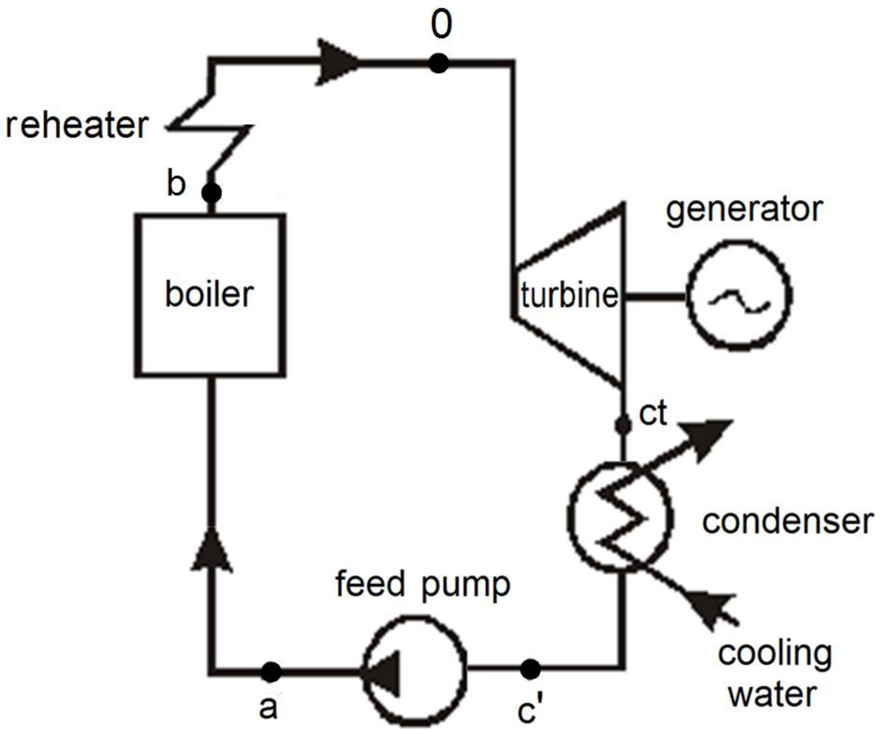
0-ct – isentropic expansion of the steam in a turbine

0-c – actual process of expansion of steam with respect to energy losses

c-c' – isobaric heat removal in a condenser, condensation of steam

c'-a – isentropic compression of a liquid in a pump

Rankine cycle with reheated steam



a-0 – isobaric heat supply to a working medium at initial pressure $p_0 = const$

a-b – heating water to a boiling point and steam generation, isobaric-isothermal process at $p_0 = const$ and saturation temperature $T_0 = const$

b-0 – reheating of steam at $p_0 = const$

c'-a – isentropic compression of a liquid in a pump

Rankine cycle with reheated steam

In an ideal Rankine cycle with reheated steam for 1 kg:

$q_1 = h_0 - h_a$ → Quantity of the heat supplied

$q_2 = h_{ct} - h_c{}'$ → Quantity of the heat removed

$l_{cycle} = q_1 - q_2$ → Specific work of the cycle

$l_{cycle} = l_{turbine} - l_{pump}$ → Work as difference between the work of the turbine and the work of the pump

$l_{turbine} = H_0 = h_0 - h_{ct}$ → Work in the turbine

$l_{pump} = h_a - h_c{}'$ → Work in the pump

Rankine cycle with reheated steam

Work of the cycle $l_{cycle} = (h_0 - h_{ct}) - (h_a - h_c')$

Theoretical turbine capacity $N_0 = G \cdot H_0$

where *G* is steam consumption for the turbine (in *kg/s*)

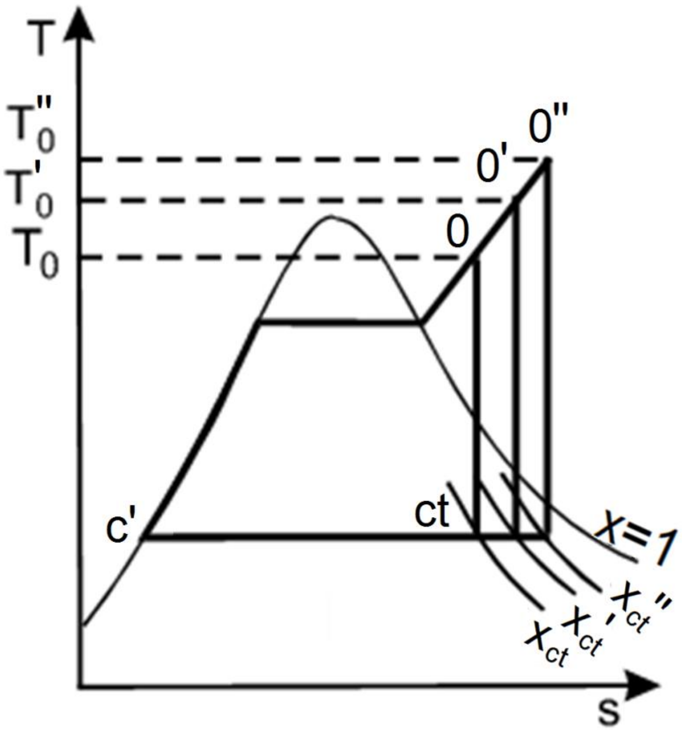
$$\boxed{\eta_t^{Rankine} = \frac{q_1 - q_2}{q_1} = \frac{l_{cycle}}{q_1} = \frac{(h_0 - h_{ct}) - (h_a - h_c')}{h_0 - h_a}}$$

Thermal efficiency of the Rankine cycle with reheated steam

Results of the shift to reheated steam

- Thermal efficiency of the cycle with reheated steam is always superior to thermal efficiency of the cycle with saturated steam at the same p_0
- Steam turbine is constructed more easily (steam consumption is reduced)
- All the equipment is cheaper

Impact of initial temperature T_0 on thermal efficiency of the Rankine cycle



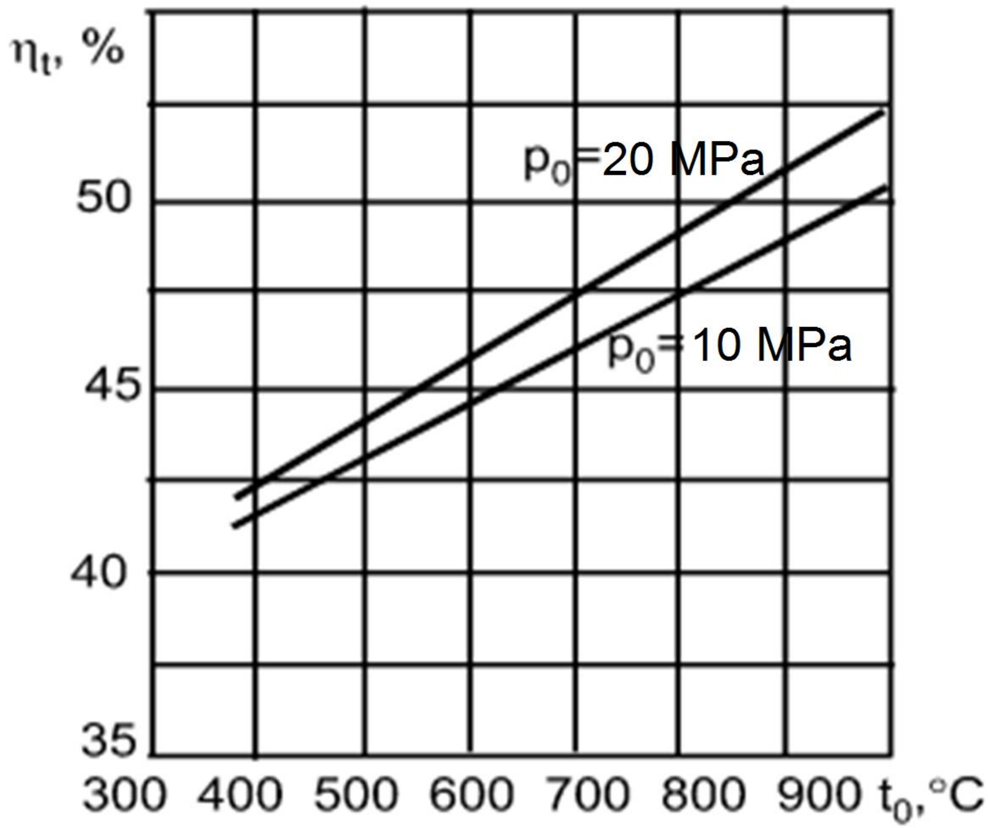
$$p_0 = const, \quad p_c = const$$

$$T_0'' > T_0' > T_0$$

$$x_{ct}'' > x_{ct}' > x_{ct}$$

Degree of dryness of steam at the end of the process of expansion *increases* with increasing temperature T_0 (humidity decreases).

Impact of initial temperature T_0 on thermal efficiency of the Rankine cycle



Impact of initial temperature T_0 on thermal efficiency of the Rankine cycle

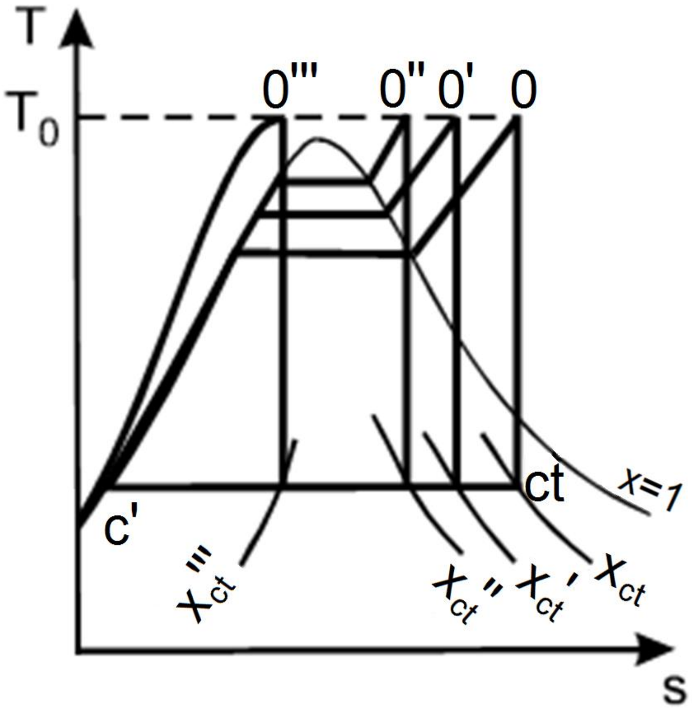
Conclusion:

1) Increase of T_0 always causes thermal efficiency to increase because the average temperature of heat supply in the cycle increases

2) Increase of T_0 causes the degree of dryness at the outlet of the flow section of the turbine to increase. As a result, losses caused by humidity decrease, and relative internal efficiency of the turbine increases.

3) Increase of T_0 makes the equipment more expensive (capital costs of more expensive materials rise)

Impact of initial pressure p_0 on thermal efficiency of the Rankine cycle



$$T_0 = const, \quad p_c = const$$

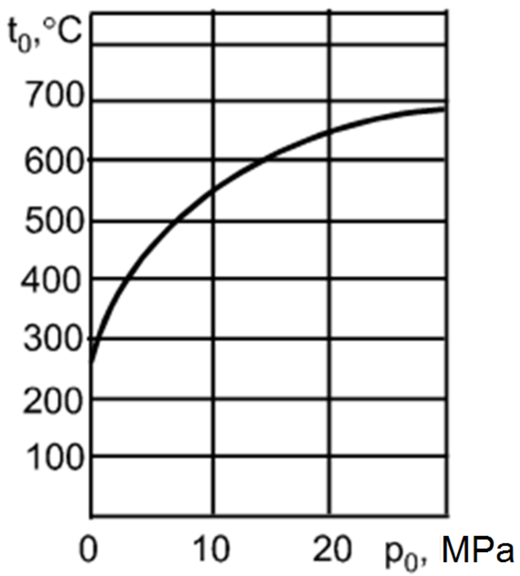
$$p_0''' > p_0'' > p_0' > p_0$$

$$x_{ct}''' > x_{ct}'' > x_{ct}' > x_{ct}$$

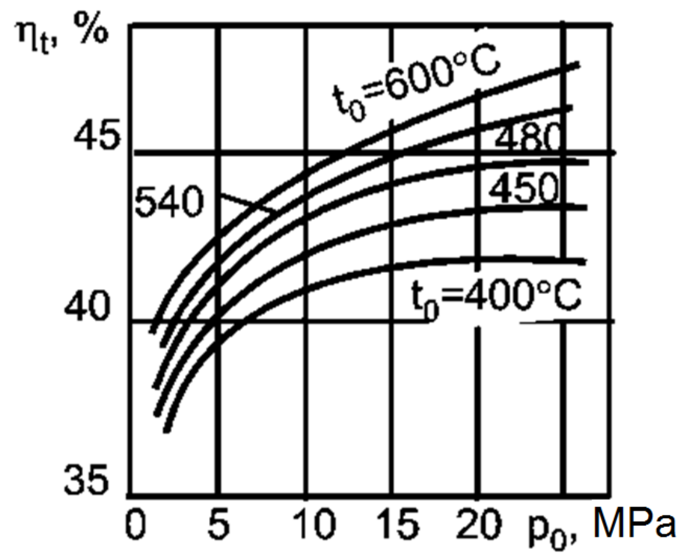
Increase of p_0 is accompanied by *displacement of line of isentropic expansion* to the left, which causes humidity of exhaust steam to increase

Impact of initial pressure p_0 on thermal efficiency of the Rankine cycle

In order *not to exceed the ultimate humidity of the exhaust steam,* it is necessary to increase simultaneously temperature and pressure.



Dependence between p_0 and T_0



Change of efficiency with increase of p_0

Impact of initial pressure p_0 on thermal efficiency of the Rankine cycle

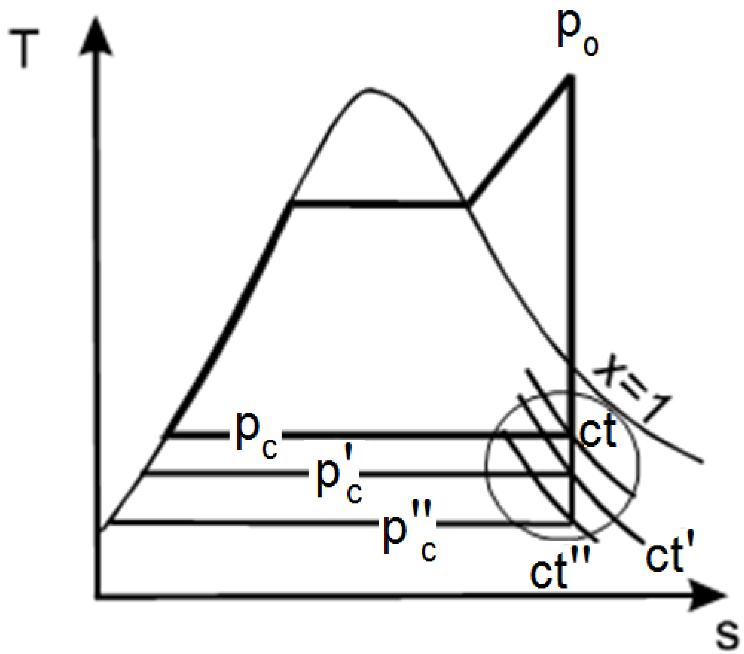
Conclusion:

1) On the one hand, increase of pressure p_0 (up to some value) causes thermal efficiency of the cycle of a steam-turbine plant to increase.

2) On the other hand, this increase of pressure causes *the degree of dryness* at the outlet of the flow section of the turbine to *decrease.* As a result, relative internal efficiency decreases.

3) Increase of pressure *makes the equipment more expensive* (the wall becomes thicker, capital costs rise)

Impact of pressure in condenser p_c on thermal efficiency of Rankine cycle



Rankine cycle at various final pressures (in Ts-diagram)

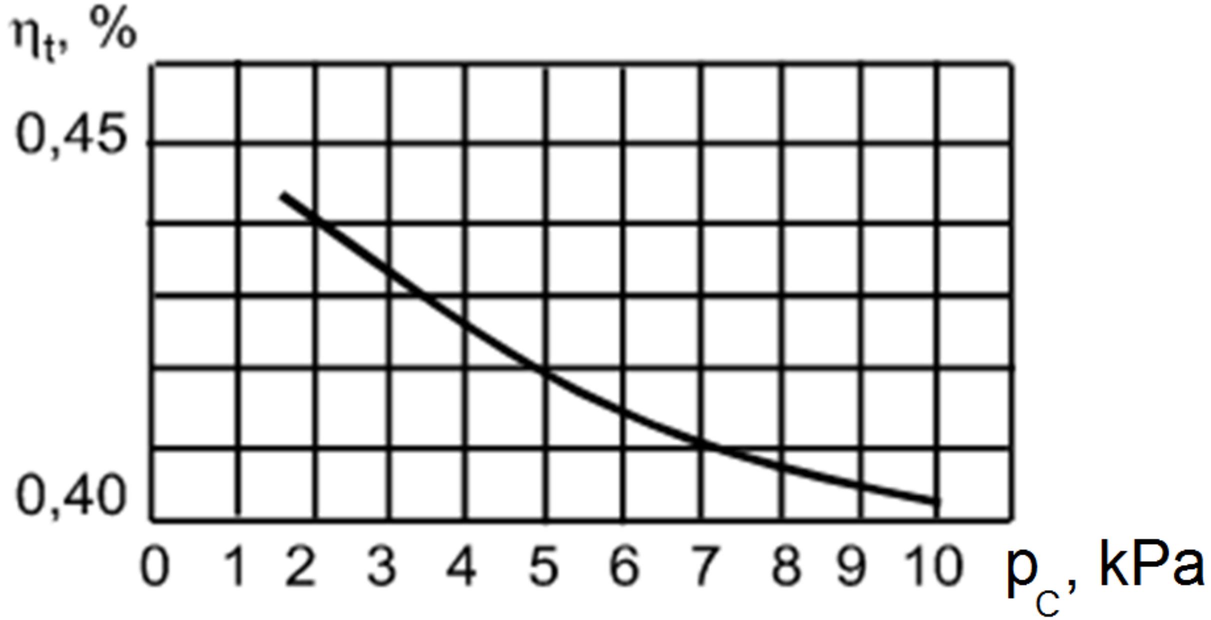
$$T_0 = const, \quad p_0 = const$$

$$p_c > p_c' > p_c''$$

$$x_{ct} > x_{ct}' > x_{ct}''$$

At decreased pressure, the humidity of steam increases at the end of the expansion process

Impact of pressure in condenser p_C on thermal efficiency of Rankine cycle



Dependence of efficiency of the Rankine cycle on the final pressure

Impact of pressure in condenser p_c on thermal efficiency of Rankine cycle

Conclusion:

1) Decrease if the final pressure causes *thermal efficiency to increase* because heat losses in the cycle decrease.

2) At decreased pressure *at the outlet of the turbine, the steam humidity increases* at the end of the expansion process, which leads to increase of losses in the turbine.

3) *Capital costs rise* when trying to approximate the temperature of steam in a condenser to the temperature of cooling water (expansion of heat-exchange surface)

Cycles of nuclear power plants

Thermodynamic cycles of steam-turbine plants of NPP are mostly conditioned by the **steam generating plant**, the main component of which is nuclear reactor

Above all, the features of work and structure of the nuclear reactor condition the value of initial parameters of steam of the steam-turbine plant

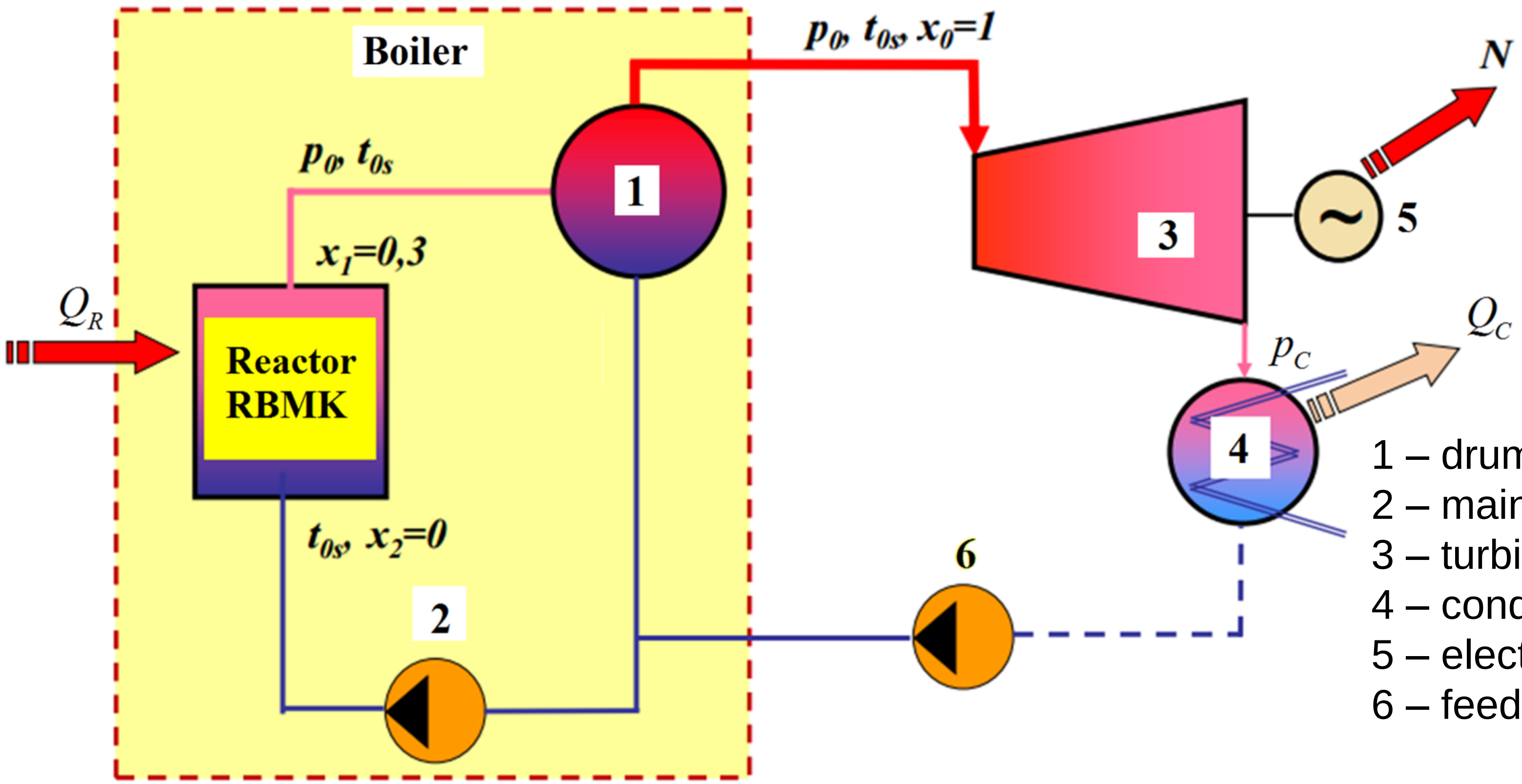
Nuclear reactors can be divided into:

- Thermal
- Fast
- Intermediate

Thermal-neutron one/two-circuit reactors are used most worldwide

Cycles of nuclear power plants

a) *scheme of one-circuit NPP*



1 – drum separator
2 – main circulating pump
3 – turbine
4 – condenser
5 – electrical generator
6 – feed pump

Cycles of nuclear power plants

In Russia (the Soviet Union) one-circuit NPP is based on RBMK types of reactor.

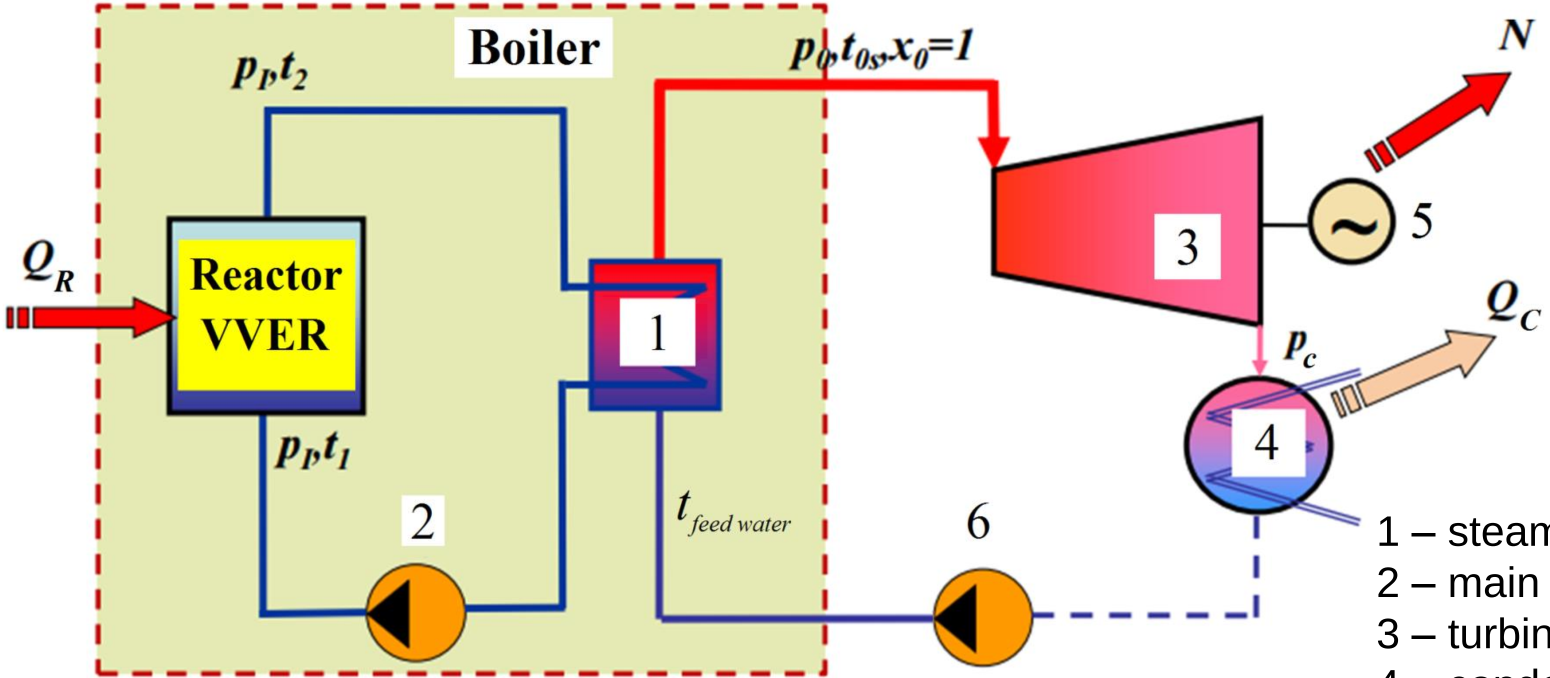
In total, 17 units were constructed
(15 – RBMK-1000 and 2 – RBMK-1500)

In other countries, this scheme was performed based on reactors BWR – Bowling Water Reactor

29 power units – in the United States
35 power units – in other countries

Cycles of nuclear power plants

b) *scheme of two-circuit NPP*



1 – steam generator
2 – main circulating pump
3 – turbine
4 – condenser
5 – electrical generator
6 – feed pump

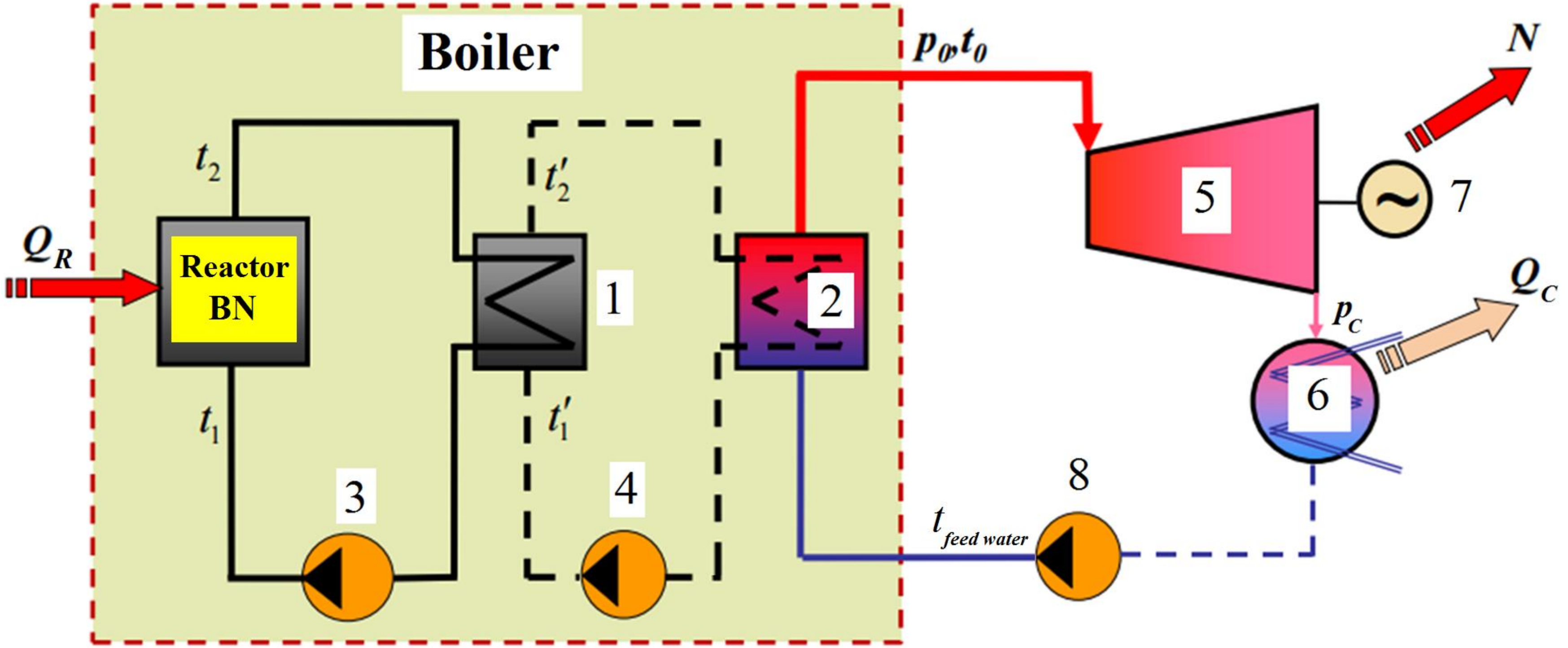
Cycles of nuclear power plants

In Pressurized Water Reactor (PWR), light water is used as a neutron moderator and a coolant. This type of reactor is used most worldwide.

Russia constructs reactors of VVER («ВВЭР») type

Cycles of nuclear power plants

c) *scheme of three-circuit NPP*



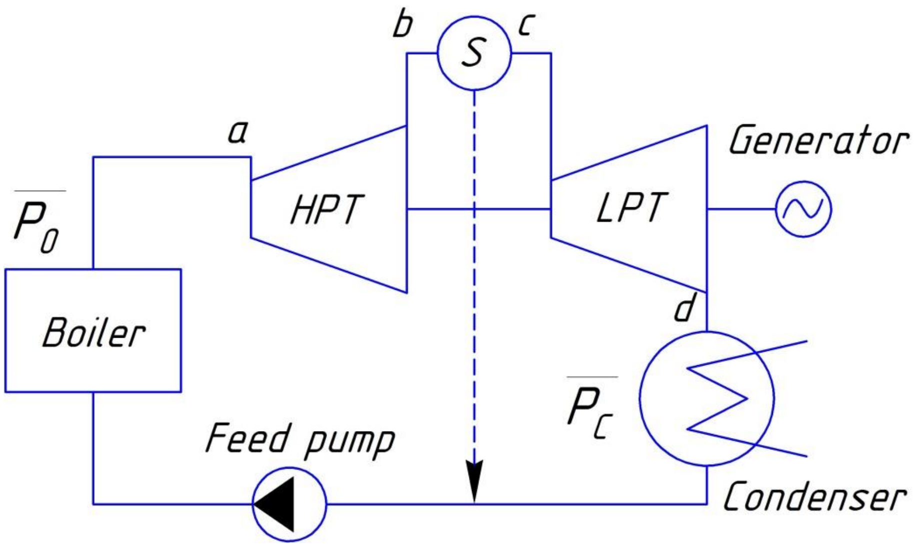
1 – heat exchanger; 2 – steam generator; 3 – main circulating pump *1*; 4 – main circulating pump *2*; 5 – turbine; 6 – condenser; 7 – electrical generator; 8 – feed pump

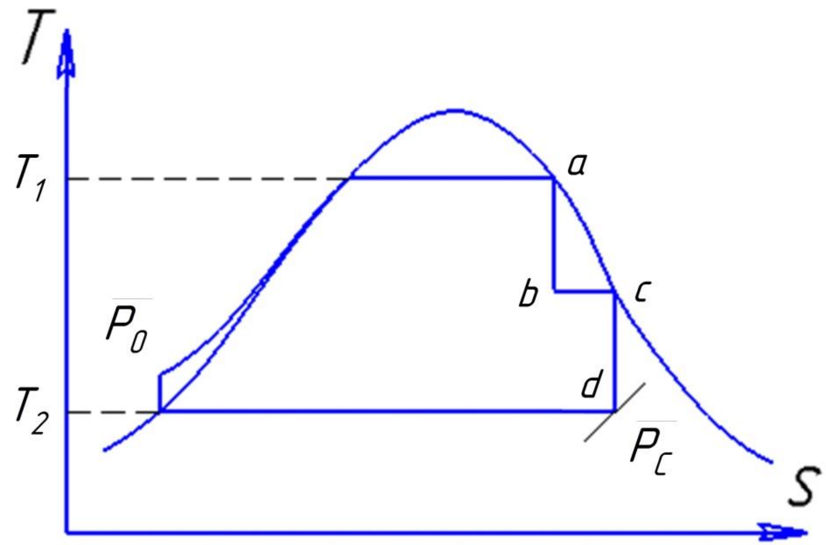
Cycle of power plant with a moisture separator

Cycle of steam-turbine plants in NPP includes intermediate moisture-separation. Steam, having reached the limit values of humidity during expansion in a High-pressure turbine, is removed in moisture-separator and dried in it at constant pressure.

Intermediate moisture-separation *increases useful work*, but simultaneously it increases heat removal in the cold source.

Diagram of NPP with moisture separator





HPT – High Pressure Turbine
LPT – Low Pressure Turbine
S – moisture separator

Coefficient of separation:

$$\gamma = \frac{\Delta y}{y_0} = \frac{x_c - x_b}{1 - x_b}$$

$$\gamma = 0{,}97 - 0{,}99$$

Thermal efficiency of NPP with moisture separator

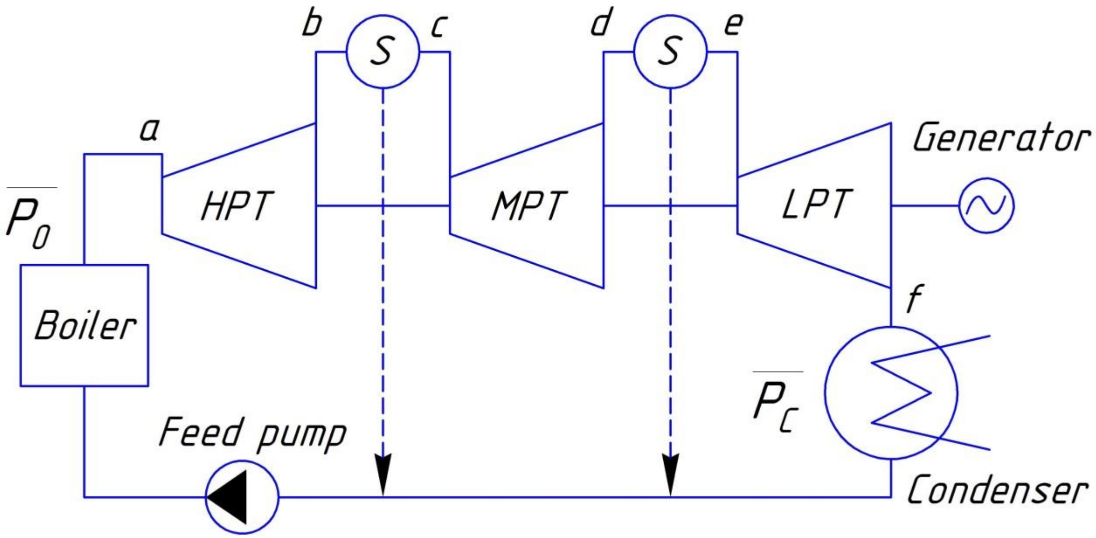
$$\boxed{\eta_t = \frac{N_0}{G_0 \cdot (h_0 - h_{feed\,water})}}$$

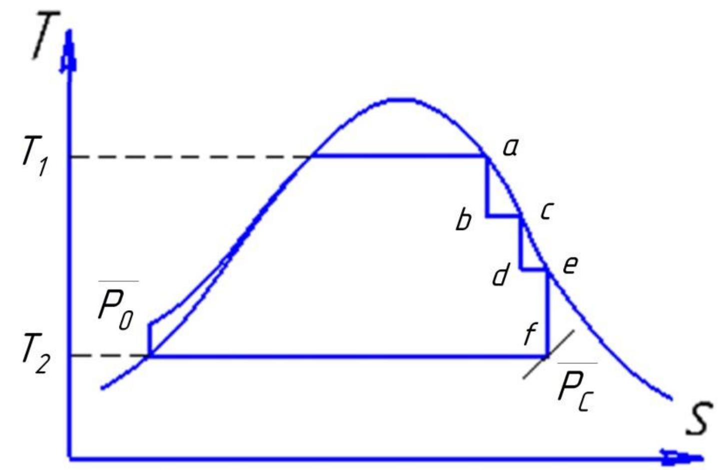
N_0 – maximal capacity of the turbine

G_0 – steam consumption for the turbine

When the separated moisture is removed to the line of the main condensate, which is heated by mixed flows, there is *heat recovery*. Due to this, the efficiency of the installation with separation is higher than that in the original Rankine cycle at the same initial and final values of pressure

Diagram of NPP with two moisture separators





HPT – High-pressure turbine
MPT – Medium-pressure turbine
LPT – Low-pressure turbine
S – moisture separator

Cycle of power plant with two moisture separators

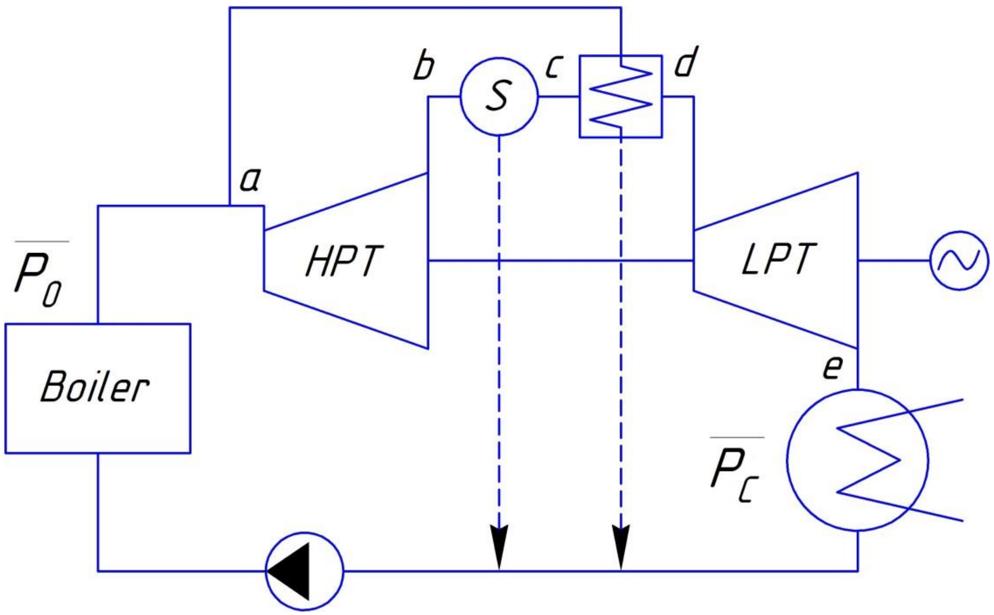
From technical and economic point of view, deep drying is not reasonable. Steam separation to dryness degree $x \approx 0{,}86$ is enough. Beyond this limit, the required amounts of separation equipment, already big, dramatically increase because through them the full steam flow passes from a high-pressure turbine

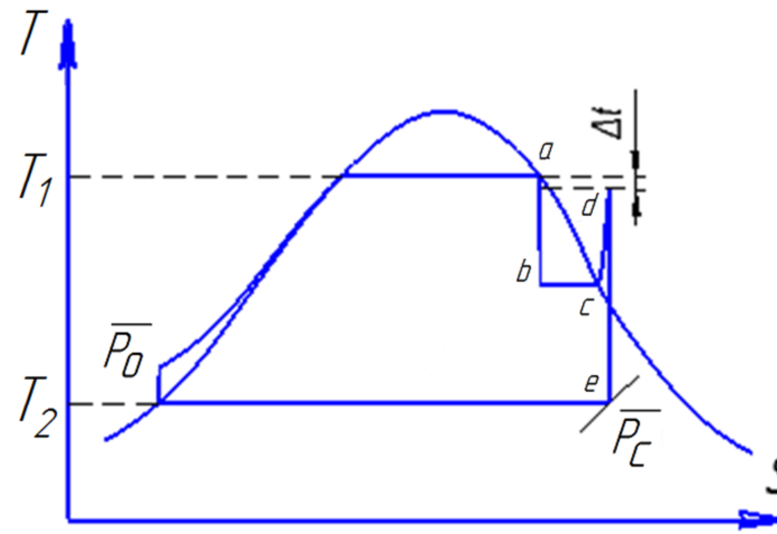
Cycle of power plant with a moisture separator-reheater

Steam reheating in the turbine allows avoiding high humidity at the end of the expansion process at high initial steam parameters. It prevents erosive wear of turbine paddles; steam losses in the turbine decrease; and, consequently, relative internal efficiency increases.

Higher value of the turbine capacity is an advantage of steam-turbine plant with reheating.

Diagram of NPP with a moisture separator-reheater





HPT – High Pressure Turbine
LPT – Low Pressure Turbine
S – moisture separator

Cycle of power plant with a moisture separator-reheater

$$\boxed{\eta_t = \frac{N_0}{(G_0 + G_{RH}) \cdot (h_0 - h_{feed\ water})}}$$

N_0 – maximal capacity of the turbine

G_0 – steam consumption for the turbine

G_{RH} – steam consumption for the reheat

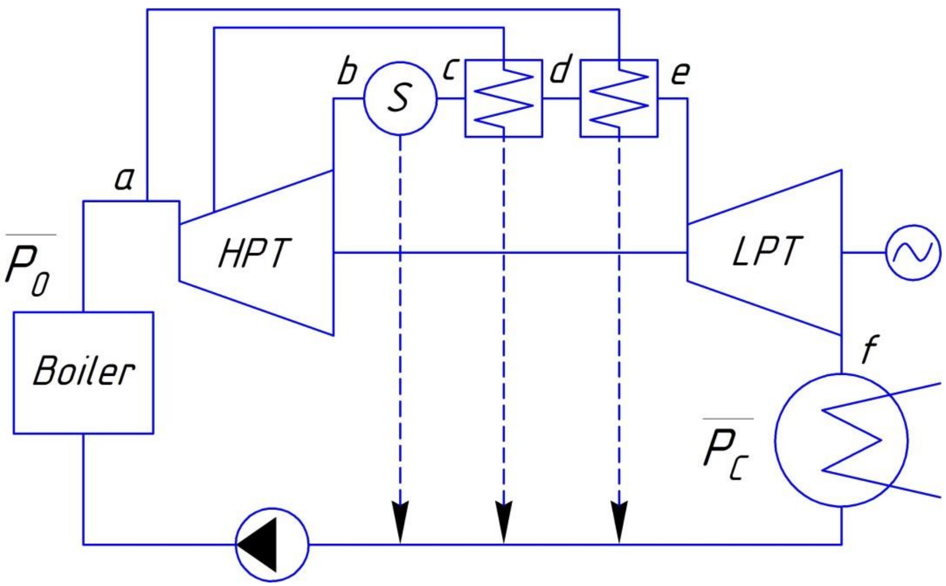
Correct choice of reheating pressure allows increase in the efficiency of the cycle due to increased average temperature of heat supply.

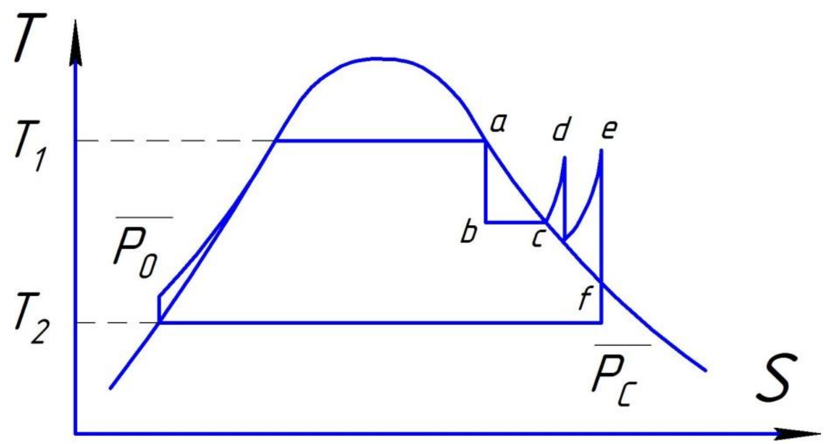
Cycle of power plant with a moisture separator and two reheaters

Repeated reheating is possible. However, each additional stage of reheating leads to loss of pressure, additional cost, and installation becomes more complicated. Two-time reheating in plants increases thermal efficiency by 6…7%.

However, nowadays repeated reheating is unreasonable *because of the high cost of expensive high-temperature items.*

Diagram of NPP with a moisture separator and two reheaters





HPT – High Pressure Turbine
LPT – Low Pressure Turbine
S – moisture separator

THANK YOU FOR ATTENTION