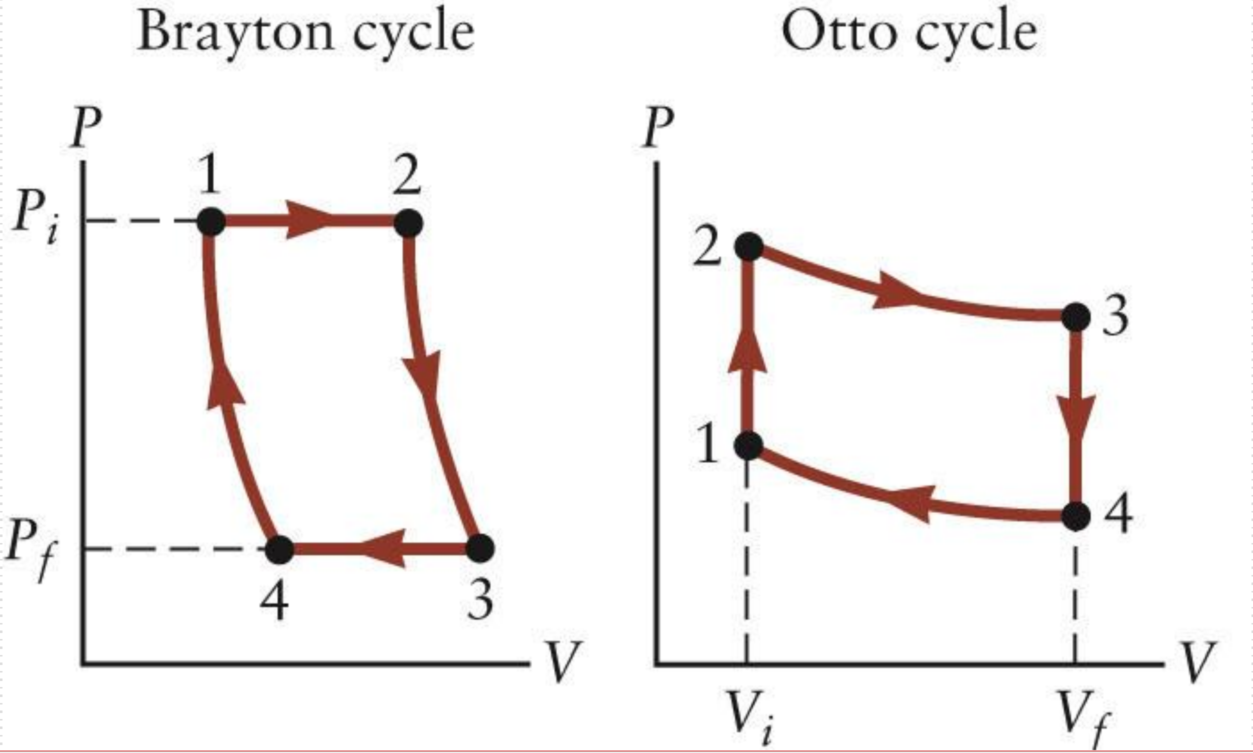
METHODS TO IMPROVE THERMAL EFFICIENCY OF GAS AND STEAM TURBINE PLANT

Increasing thermal efficiency of perfect gas cycles

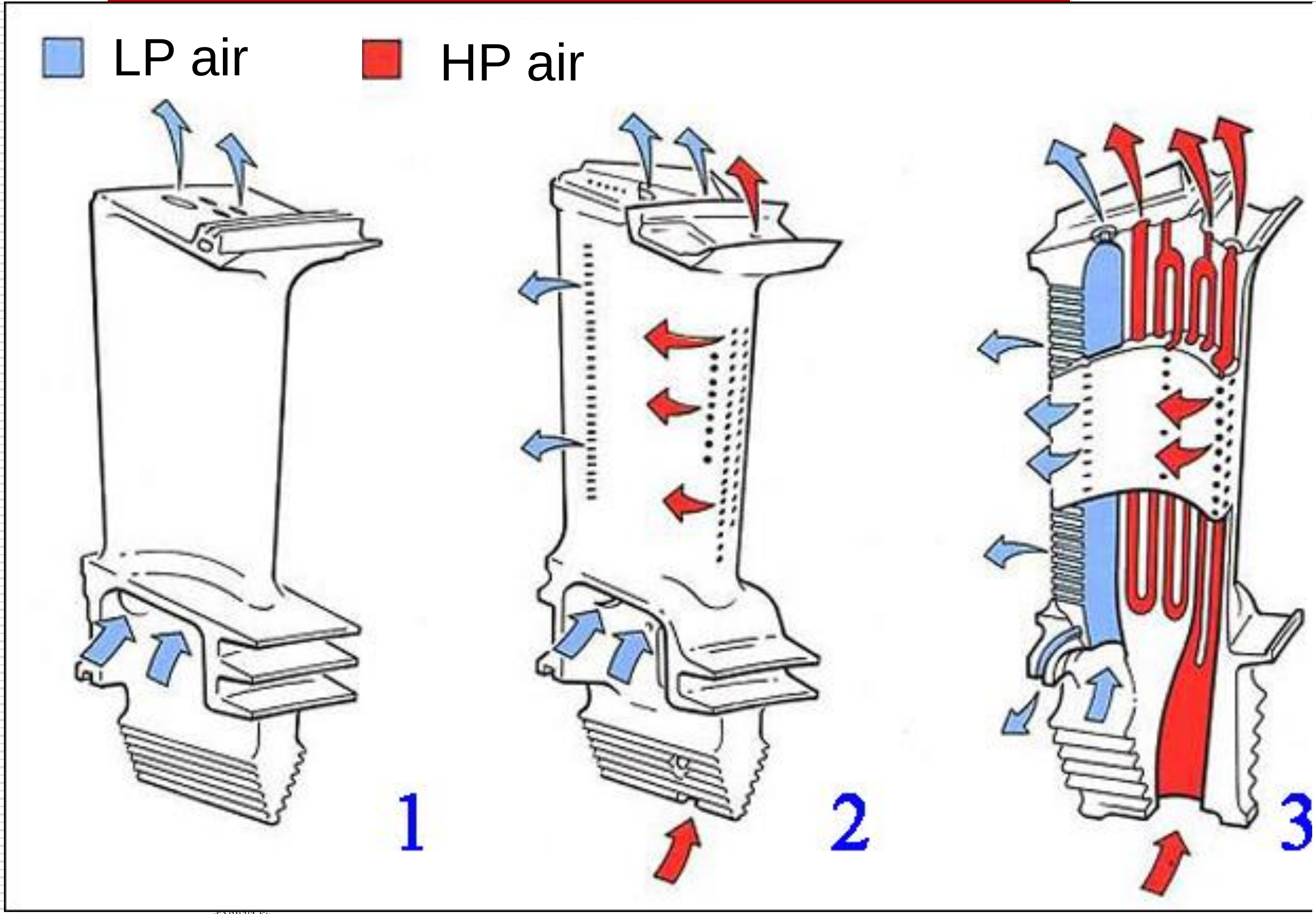
1. Increasing initial temperature of gas before expansion
2. Fitting the pressure of gas before expansion
3. Multistage compression and expansion
4. Decreasing temperature of heat rejection
    a. Regeneration
    b. Supplementary Rankine cycle

Temperature before expansion

- Increasing temperature of working fluid before expansion (points 2 for Brayton and Otto cycles) means increasing temperature of hot energy source.



Temperature before expansion



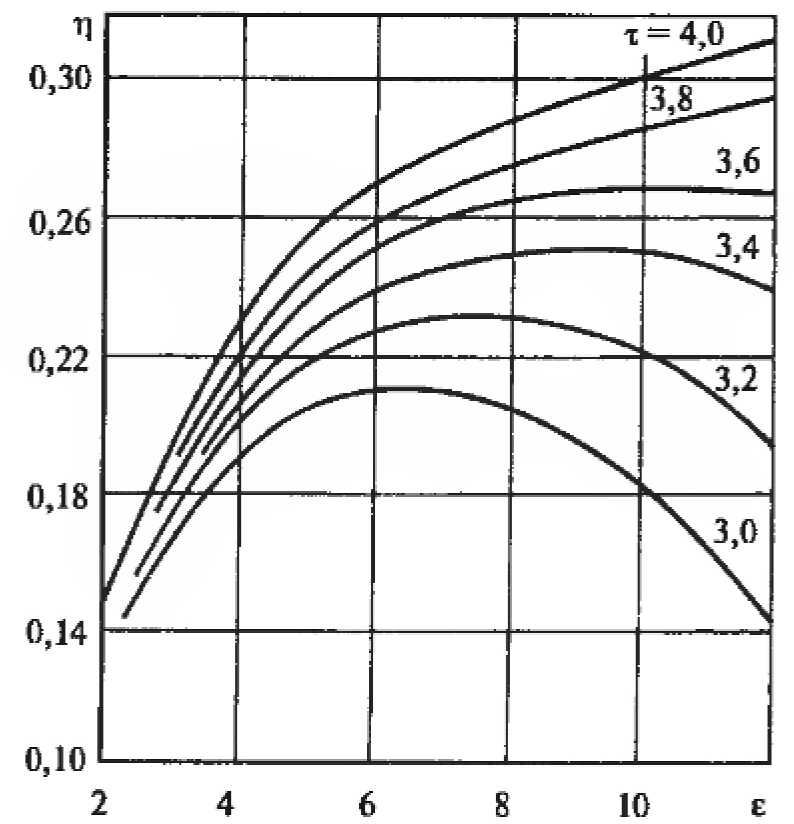
1 – convective cooling

2 – combined convective-film cooling

3 - combined convective-film cooling with complex form of channel for additional conductive cooling

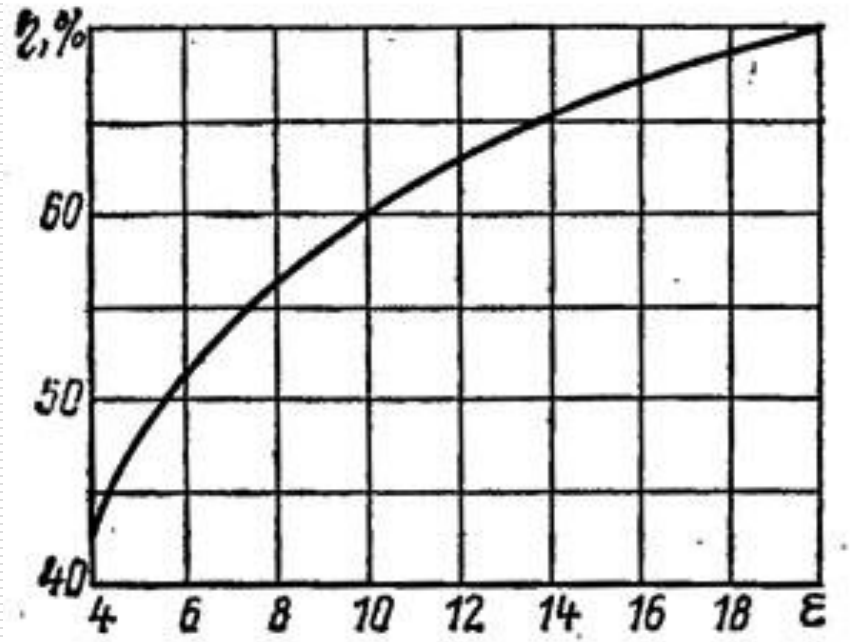
Pressure before expansion

- The Brayton cycle as well as Otto cycle has optimal pressure increase ratio depending on temperature increase ratio and internal efficiency of turbine and compressor. In real conditions, efficiency of compressor quickly decreases with increasing compressor ratio. It shifts practical optimum into lower compression ratio compared to theoretical value.



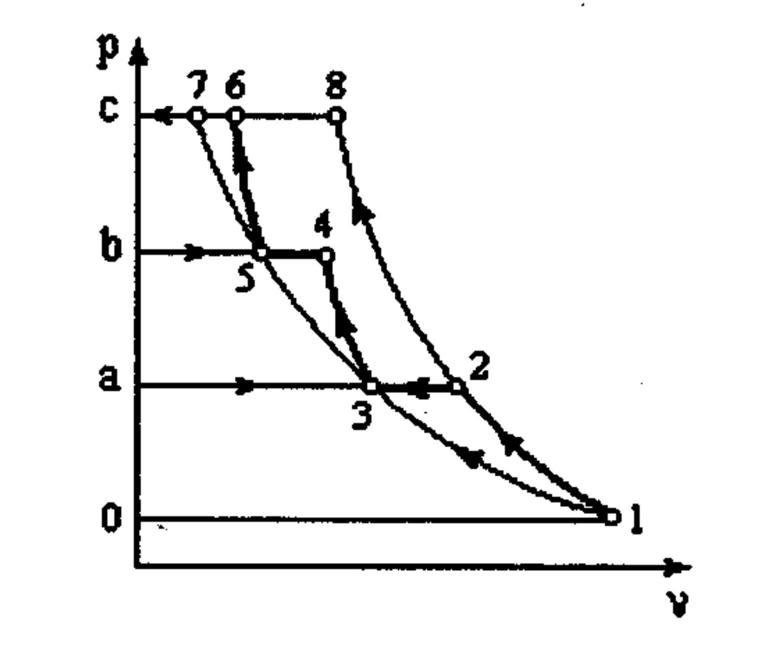
Pressure before expansion

- Optimal compression ratio is defined by technic-economical calculation. It appear at the area with lower efficiency increasing with growing compression ratio.
- For Otto cycle increasing compression ratio is linearly connected to increasing size of engine. In this case, to increase final pressure of cycle and specific power of engine the additional compression on the inlet is used.



Multistage compression

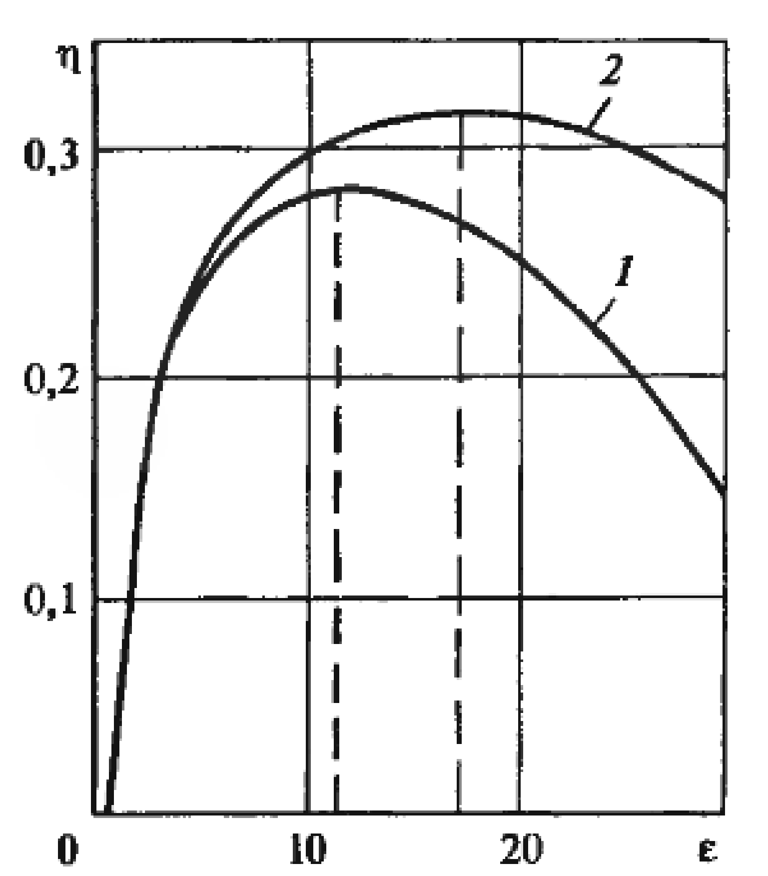
- The energy spent on compression in perfect gas cycles consumes significant part of produced work during expansion. In order to reduce this value by using the two- or three-staged compression with intermediate cooling.



- The multistage compression results into decreasing work of compression by 1 and 2 % for compressors with high efficiency (close to 90 %).

Multistage compression

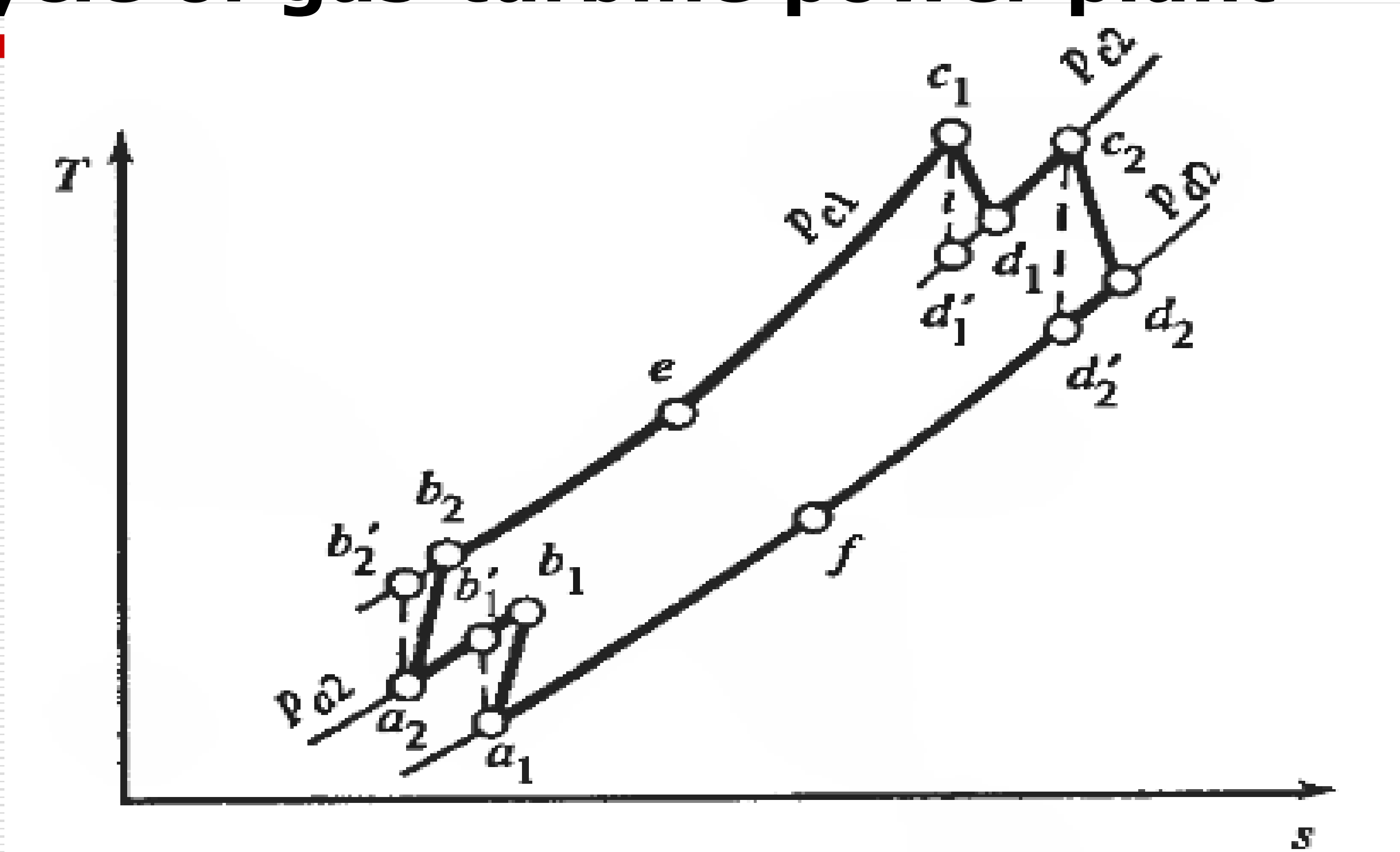
- Depending on presence/absence of element cooling in gas-turbine the efficiency of two-stage compression decreases optimal compression ratio. For simple cycle without cooling it is lower compared to cycle with cooling.
- On figure:
  - 1 – without cooling
  - 2 – with cooling



Multistage expansion

- Multistage expansion with intermediate heating is also used for increasing efficiency of turbine. The expansion ratio should be chosen using the same method as a compression rate for multistage compression.
- Multistage expansion results in the right opposite consequences compared to multistage compression:
  - increasing of produced work;
  - increasing of efficiency;
  - increasing of optimal compression ratio.

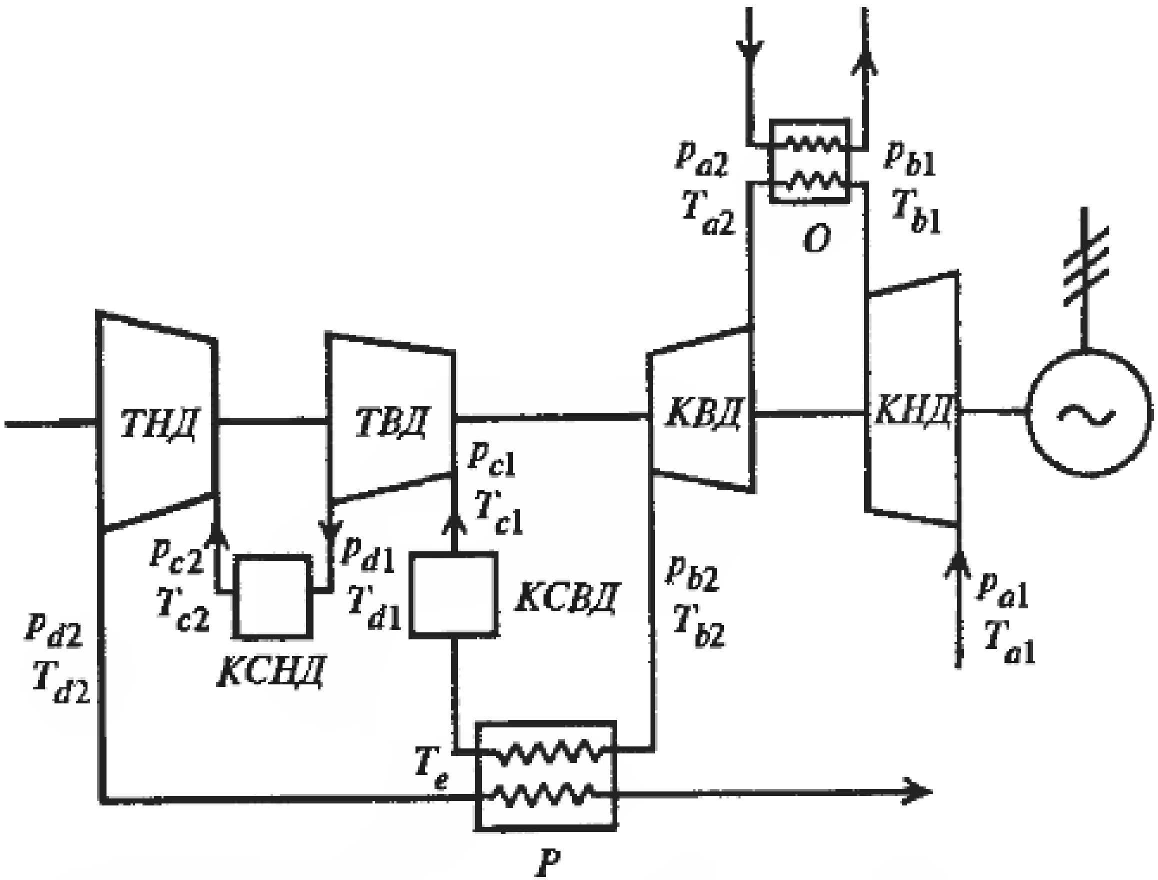
Cycle of gas-turbine power plant



- Cycle of gas-turbine power plant with two-stage compression and expansion with regeneration.

Cycle of gas-turbine power plant

- Scheme of one shaft gas-turbine power plant with two-stage compression and expansion with regeneration.



Dependence of gas-turbine power plant efficiency with two stage compression and expansion

$$\eta = \frac{\left(1-\delta_1^{-m_\text{г}}\right)\eta_{\text{т}1} + \tau_c\left(1-\delta_2^{-m_\text{г}}\right)\eta_{\text{т}2} - \dfrac{\varepsilon_1^{m_\text{в}}-1}{\tau_1\eta_{\text{к}1}} - \dfrac{\varepsilon_2^{m_\text{в}}-1}{\tau_2\eta_{\text{к}2}}}{\tau_c - \dfrac{1}{\tau_2} + \left(1-\delta_1^{-m_\text{г}}\right)\eta_{\text{т}1} - \dfrac{\varepsilon_2^{m_\text{в}}-1}{\tau_2\eta_{\text{к}2}} - \sigma\left[\tau_c - \tau_c\left(1-\delta_2^{-m_\text{г}}\right)\eta_{\text{т}2} - \dfrac{1}{\tau_2} - \dfrac{\varepsilon_2^{m_\text{в}}-1}{\tau_2\eta_{\text{к}2}}\right]},$$

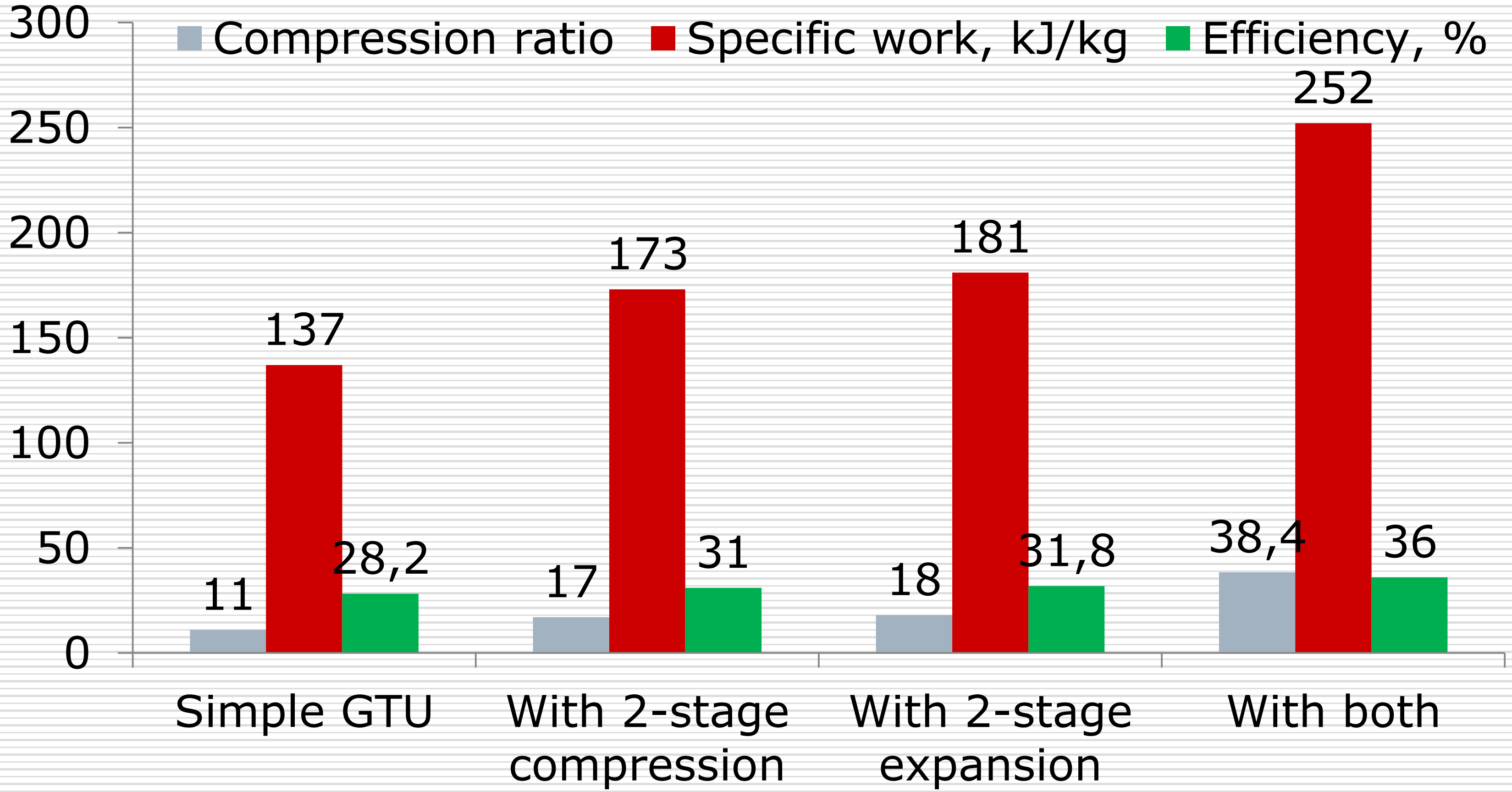
ε – compression ratio

δ – expansion ratio

τ – temperature increasing ratio

η – efficiency of turbine and compressor

Parameters of simple and modified gas-turbine power plant

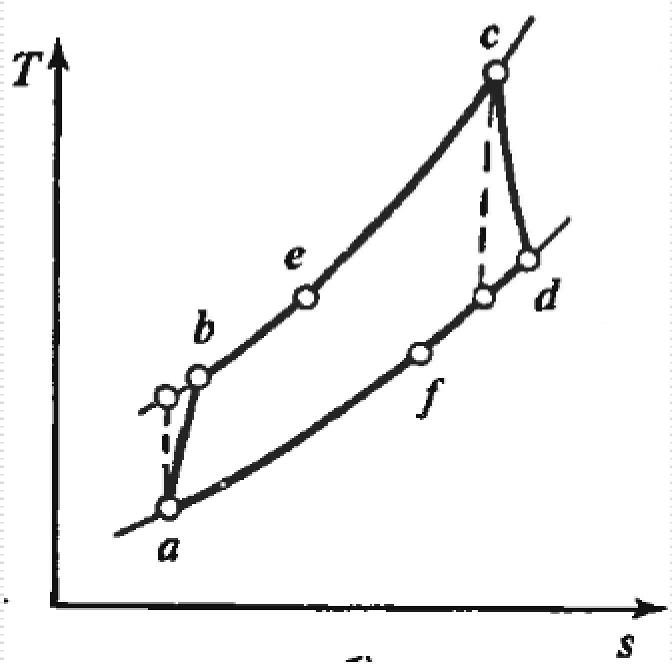


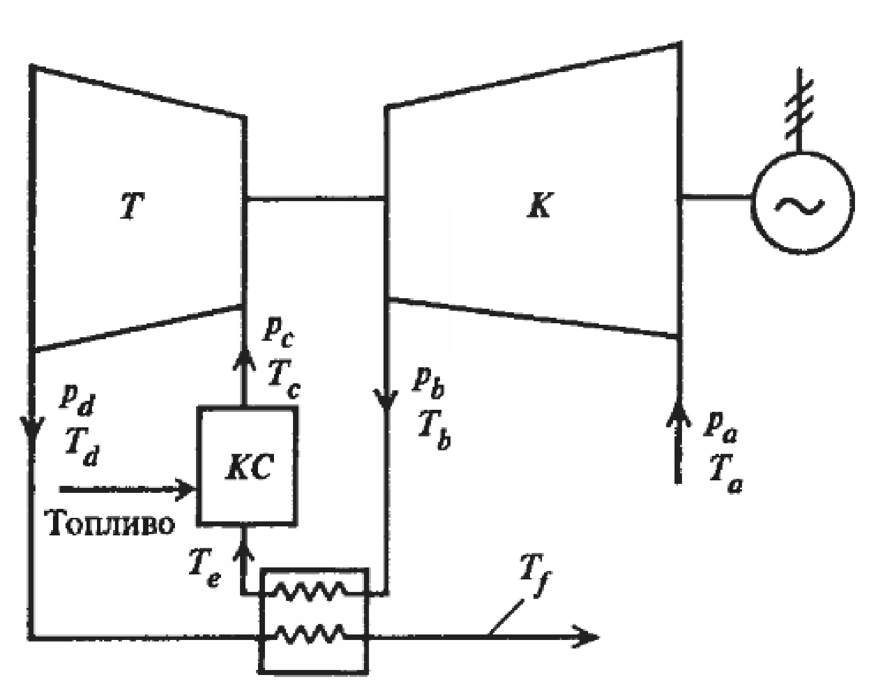
Heat rejection temperature
Regeneration

- Regeneration – process of heating of inlet air by exhaust gases.
- As long as slope of isochoric process in Ts-diagram is significantly lower compared to slope of isobaric process. This reduces outlet gas temperature compared to inlet air after compression and reduces possibilities for regeneration application. Lower compression ratio of Otto cycle compared to Brayton cycle resulted into more often application of regeneration systems for gas-turbine power plant working by Brayton cycle.

Regeneration for Brayton cycle

- For Brayton cycle power plant the regeneration is used to heat air after compression.





Scheme and cycle of gas-turbine power plant with regeneration

Degree of regeneration and efficiency

- Degree of regeneration is relation of the maximal possible value of heat which could be given to air after compressor to real heat.

$$\sigma=(T_e-T_b)/(T_d-T_b)$$

- The dependence of efficiency on main parameters for cycle with regeneration is given below:

$$\eta = \eta_{\text{к.с}} \frac{\bar{c}_{p\,\text{г}}\eta_{\text{т}}\left(1-\delta^{-m_{\text{г}}}\right) - \bar{c}_{p\,\text{в}}\dfrac{\varepsilon^{m_{\text{в}}}-1}{\tau\eta_{\text{к}}}}{1-\dfrac{1}{\tau}\left(1+\dfrac{\varepsilon^{m_{\text{в}}}-1}{\eta_{\text{к}}}\right)\sigma\left[1-\eta_{\text{т}}\left(1-\delta^{-m_{\text{г}}}\right)-\dfrac{1}{\tau}\left(1+\dfrac{\varepsilon^{m_{\text{в}}}-1}{\eta_{\text{к}}}\right)\right]}$$

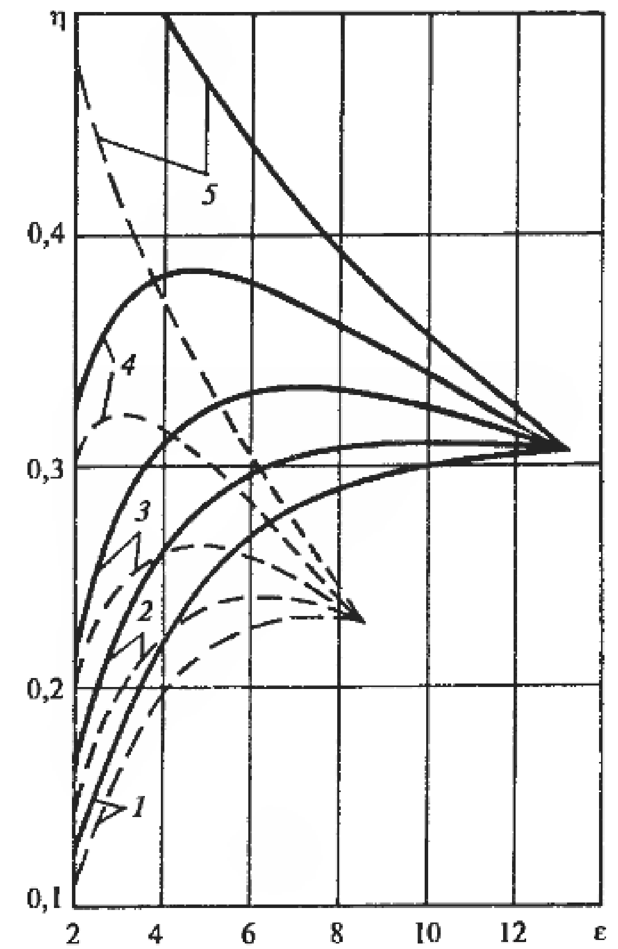
Dependence of Brayton cycle with regeneration efficiency of compression ratio

σ	0	0,5	0,75	1,00
ε	11	6,17	4,12	1
η, %	28,3	32,8	36,1	62

1 - σ=0,0
2 - σ=0,2
3 - σ=0,5
4 - σ=0,8
5 - σ=1,0

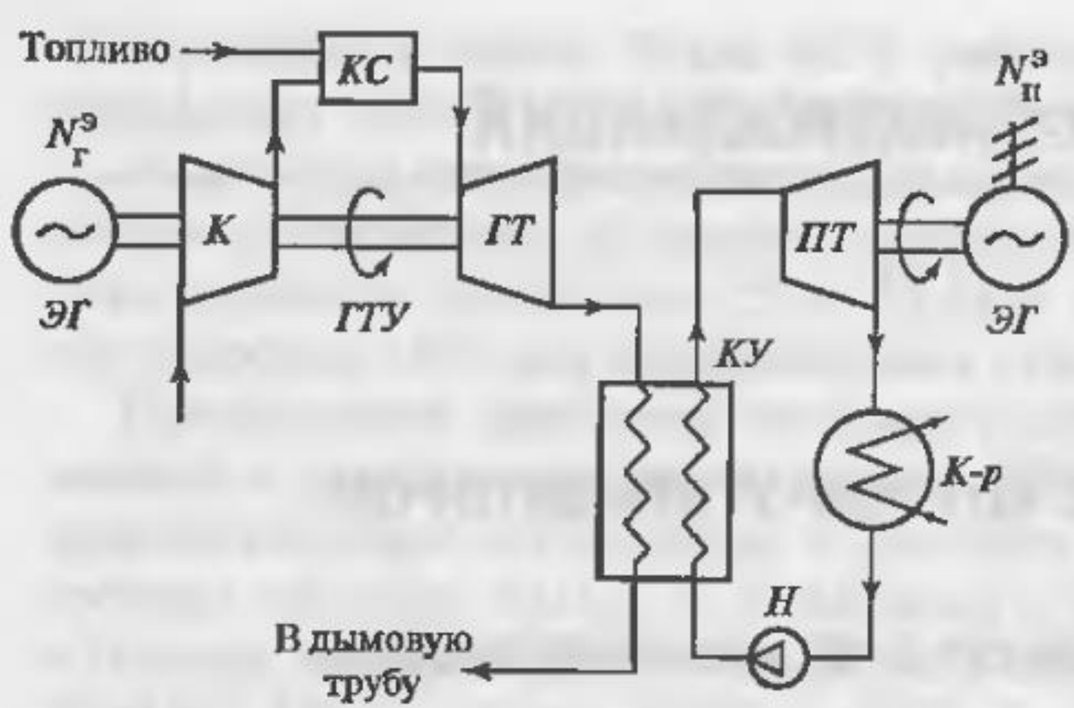
solid line - τ=4,0

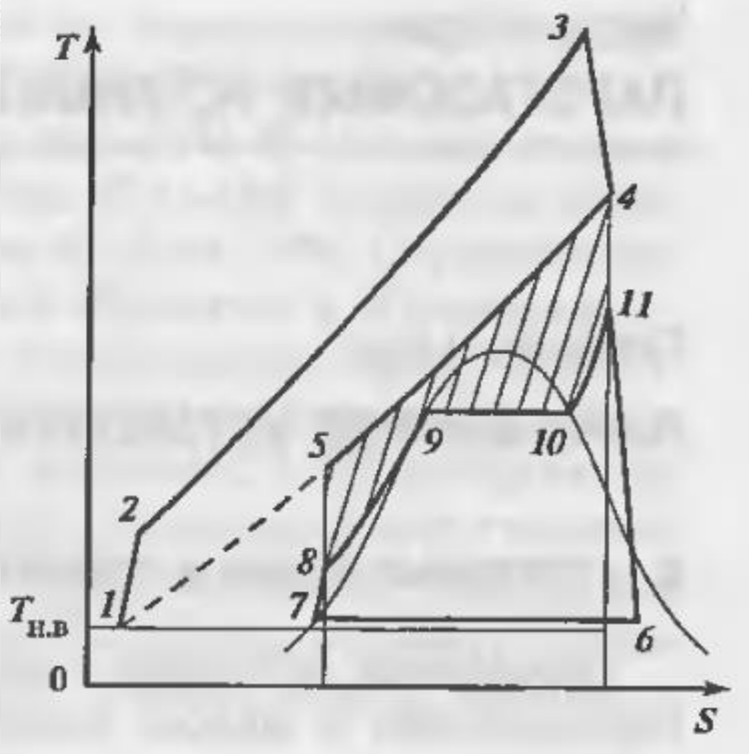
dashed line - τ=3,2



Supplementary Rankine cycle

- To reduce heat rejection temperature the supplementary Rankine cycle could be used. The cycle and scheme of such power plant is given below.





Increasing thermal efficiency in a Rankine cycle

1. Increasing the initial pressure of the steam
2. Increasing the initial temperature of the steam
3. Decreasing the pressure of the steam

Increasing the efficiency of the steam turbine due to reheated steam

Intermediate steam superheating is used to increase efficiency at high values of initial pressure.

In this case, a disposable work of the turbine increases and the moisture vapor at the exit of the turbine reduces, which increases its relative internal efficiency.

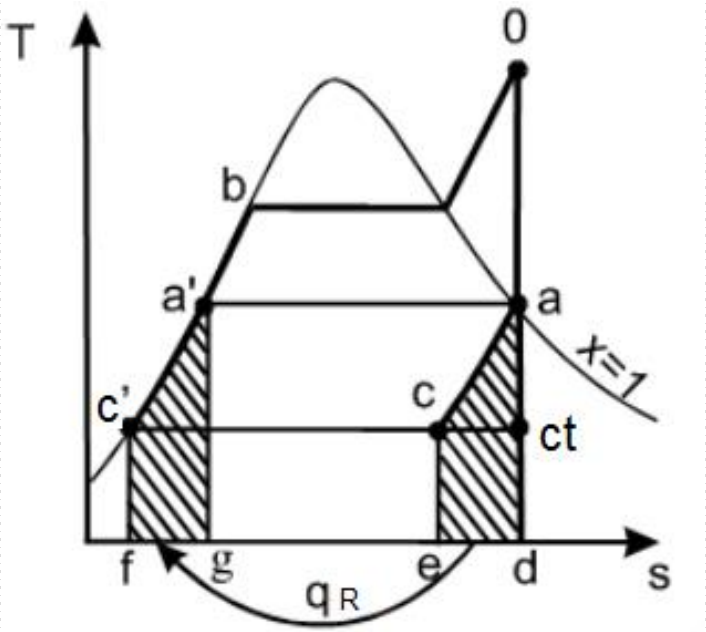
The temperature of the overheating is limited by the properties of the metal.

Regeneration of heat in cycles of the steam turbine

- To increase the efficiency of the cycle is necessary to increase the average temperature of heat supply in the cycle, therefore, increasing the temperature of the feed water is of great importance for efficiency of steam turbine installation.

- This can be achieved if you apply the principle of heat regeneration.

Regeneration of heat in cycles of the steam turbine



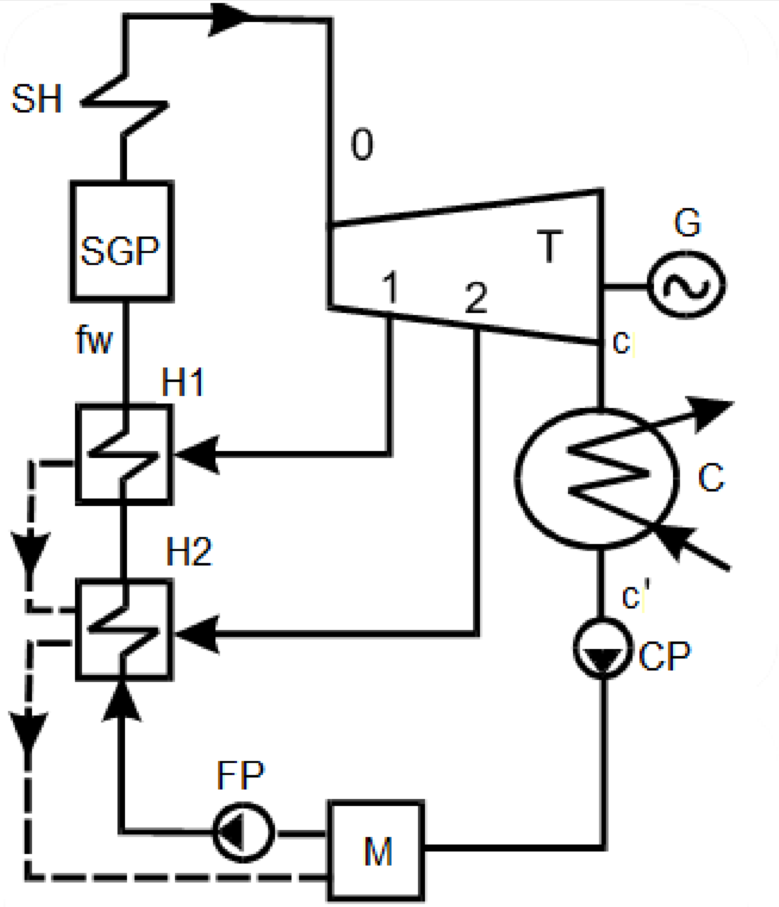
The most suitable area for regeneration is a site of heating a feed water (*c'-b*). Conducting steam expansion to (*a*), then polytrope (*a-c*), the equidistant line water heating *c'-b*, and all the emitted heat to transfer to the ideal heat exchanger water.

As a result, a feed water will be supplied with heat q_R.

Regeneration of heat in cycles of the steam turbine

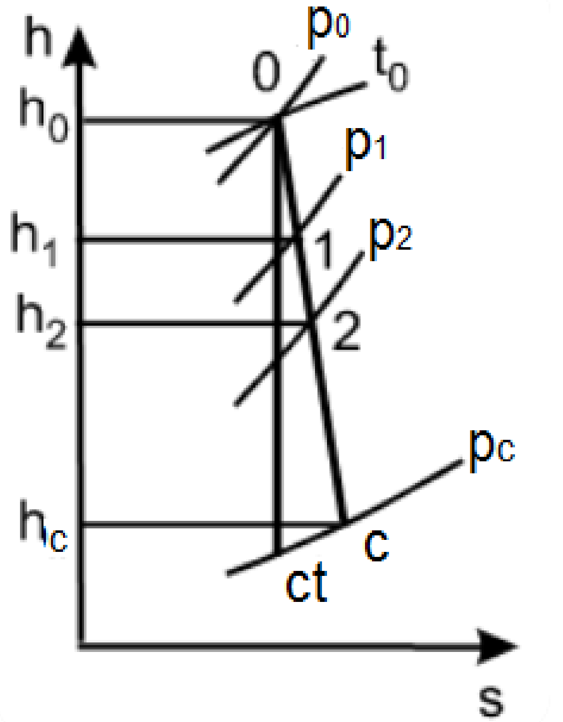
- In practice, such regeneration could not be implemented, but in a slightly different form of regenerative heating of water is widely used. This allows to significantly increase the efficiency of the cycle.

Regeneration of heat in cycles of the steam turbine



SGP– steam generating plant; **SH** –superheater; **T** – turbine; **C** – condenser; **CP** – condensate pump; **FP** – feed pump; **M** – mixer; **H1, H2** – regenerative heaters; **G** – generator; **1, 2** – the steam extractions in the turbine

Regeneration of heat in cycles of the steam turbine



1) Through the first section of the turbine all the steam goes (0-1), extending to p_1 it does work

$$l_1 = h_0 - h_1.$$

2) A share of steam a_1 with the enthalpy h_1 is taken to the heater H1, where the steam supply heat to the feed water and condenses.

3) In the second section of the turbine (1-2) the rest of the steam expands to the pressure p_2, does work

$$l_2 = (1 - \propto_1)(h_1 - h_2)$$

.

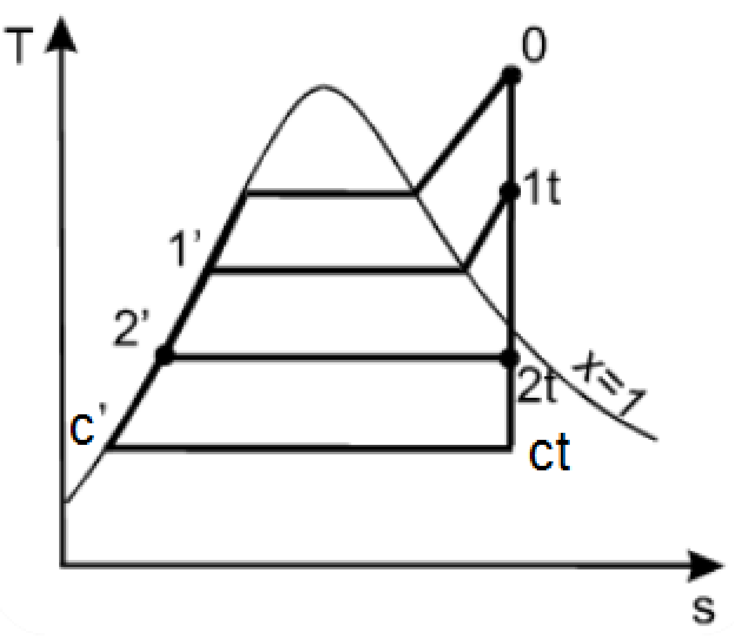
4) After expansion the steam is taken to the heater H2 with a share of steam a_2 and the enthalpy h_2.

Regeneration of heat in cycles of the steam turbine

5) The remaining a share of steam $a_c=(1-a_1-a_2)$. The steam is expanded to p_c, does work $l_c=a_c(h_2-h_c)$ and enters the condenser.

6) Then, using condensate and feed water pump, the water, heated in the mixer and the regenerative heaters, is supplied in the steam-producing installation.

Regeneration of heat in cycles of the steam turbine



0 - ct – adiabatic expansion of the steam in the turbine, s=const;
0 - 1t – process in the first section of the turbine;
1t - 2t – process in the second section of the turbine;
2t - ct – process in the third section of the turbine;
1t - 1' – extraction of heat to the heater H1, p_1=const;
2t - 2' – condensation of steam to the heater H2, p_2=const;
ct - c' – condensation of steam in condenser C, p_c=const;
c' - 0 –supply of heat to the working fluid to the mixer M, to the heaters H1, H2 and the boiler.

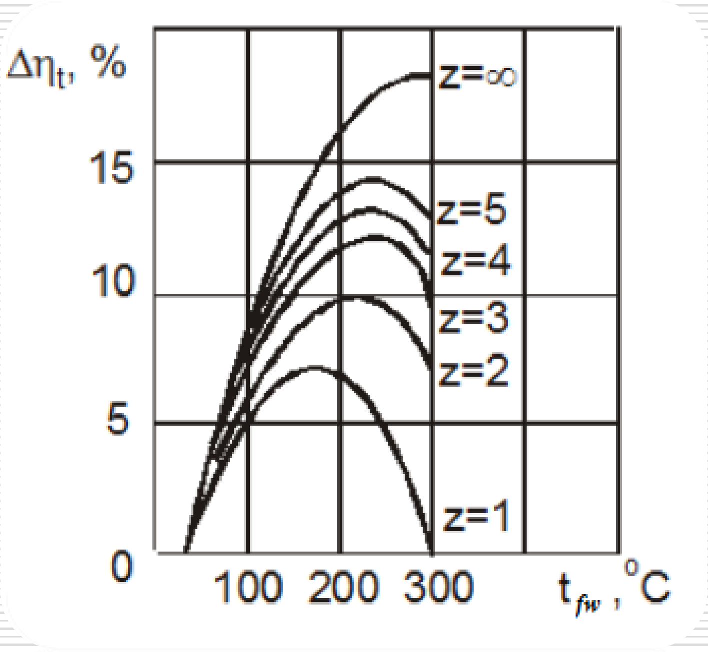
The effect of regeneration on the cycle

1) Water at the entrance to the steam generating installation has a higher temperature than the Rankine cycle. Therefore, it is necessary to supply less heat to the working fluid.

2) The steam flow to the condenser is reduced, therefore, less the loss of heat in the condenser.

3) Efficiency of regenerative heating of water depends on its parameters. It is highest for an uniform distribution of water heating on the steps.

Regeneration efficiency



A significant increase in efficiency can be obtained by applying several stages of heating

The dependence of the growth efficiency η_t on the number of regenerative feed water heaters *and* t_{fw}

Regeneration efficiency

1) The greater the number of regenerative feed water heaters, the higher the cycle efficiency.

2) Maximum efficiency is achieved at the optimal temperature t_{fw} for installing with *z*.

3) The number of regenerative feed water heaters ↑, therefore, the optimal temperature of the feed water t_{opt}↑.

4) ↑ z, therefore, the growth efficiency η_t is reduced, each subsequent selection has less impact on improving efficiency.

Calculation of consumption and efficiency of the cycle with regeneration

An ideal thermal efficiency:

$$\eta_t^R = \frac{l_R}{q_1^R} = \frac{h_0 - \sum_{j=1}^{z} \alpha_j \cdot h_{jt} - \alpha_c \cdot h_{ct}}{h_0 - h_{fw}}$$

An actual work of 1 *kg* of steam in the turbine:

$$l_i^R = H_i^R = h_0 - h_c - \sum_{j=1}^{z} \alpha_j \cdot (h_j - h_c)$$

Calculation of consumption and efficiency of the cycle with regeneration

In the previous expression, each member of the sum means the lost power of the *j*-th extraction of the steam, and the sum – is a total of lost power.

$$y_j = \frac{h_j - h_c}{h_0 - h_c}$$

The ratio of lost power

Then work of 1 *kg* of steam:

$$H_i^R = h_0 - h_c - \sum_{j=1}^{z} \alpha_j \cdot (h_j - h_c)$$

Calculation of consumption and efficiency of the cycle with regeneration

Enthalpy of feed water is determined by the balance of heat in the mixer:

$$h_{fw} = \alpha_c \cdot h_c + \sum_{j=1}^{z} \alpha_j \cdot h_j, kJ/kg$$

Then, *absolute internal efficiency* of steam turbine is equal to:

$$\eta_i^R = \frac{H_i^R}{q_1^R} = \frac{h_0 - h_c - \sum_{j=1}^{z} \alpha_j \cdot (h_j - h_c)}{h_0 - \alpha_c \cdot h_c - \sum_{j=1}^{z} \alpha_j \cdot h_j}$$

Calculation of consumption and efficiency of the cycle with regeneration

Internal power of the steam turbine with regenerative feed water heaters:

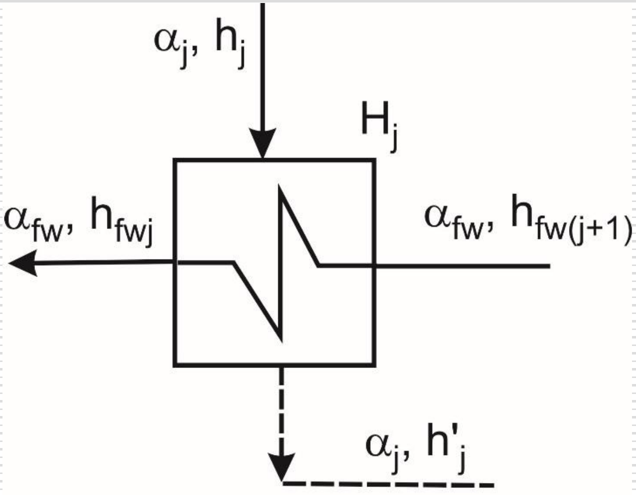
$$N_i = G \cdot H_i^R = G \cdot H_i \cdot \left(1 - \sum_{j=1}^{z} \alpha_j \cdot y_j\right), \ kW$$

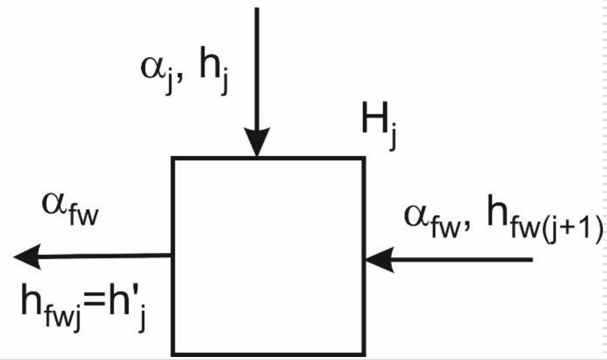
The steam consumption for a turbine:

$$G = \frac{N_i}{h_0 - h_k - \sum_{j=1}^{n} \alpha_j \cdot (h_j - h_k)} =, \ kg/s$$

Steam extractions from turbine

- To determine the share of the steam consumption, it is necessary to use the balance of heat of the heaters.





$$t_{sj} = t_{wj} + \theta$$

$$p_{Hj} = f(t_{sj})$$

$$t_{sj} = t_{wj}$$

$$p_{Hj} = f(t_{sj})$$

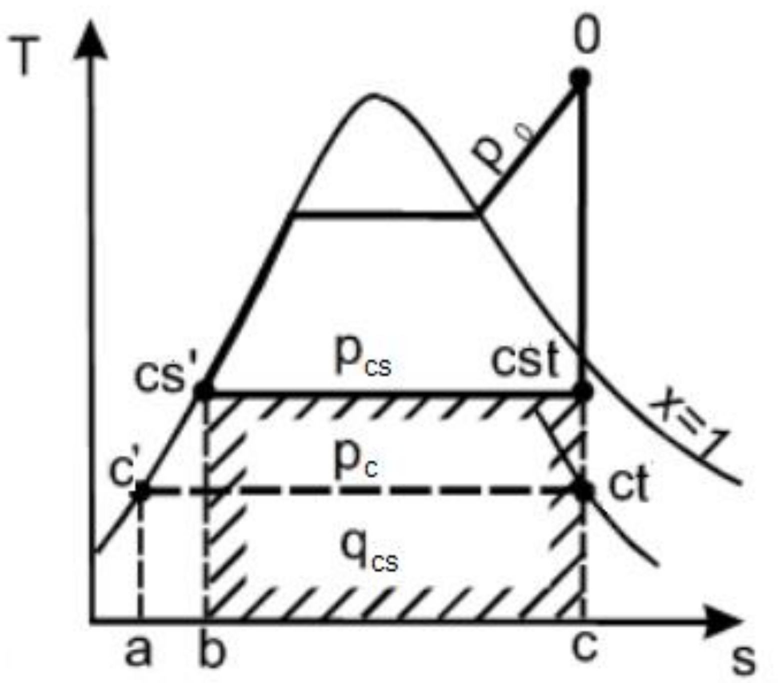
$$p_j = (0{,}97 \div 0{,}98) \cdot p_{Hj}$$

The use of district heating

The use of a cogeneration cycle is a crucial way to improve efficiency. Even the best of modern heat engines transfer heat to the cold source about half of summing up the heat.

The cycle of steam turbine installation, which supplied heat is converted into work and heat for beneficial use, is called cogeneration.
Combined production of electricity and heat at thermal power stations is called district heating (cogeneration).

The use of district heating



_0 – ct - c’ - 0_ – the cycle of condensation

0 – cst - cs’ - 0 – the cycle of district heating

The initial parameters are the same, but the specific work is different.

Pressure $p_{cs} > p_c$ и $l_{cs} < l$ in the cycle of district heating.

$q_{cs} > q_2$ – the amount of heat, which transfer heat to the cold source, increased.

The use of district heating

Using the heat of exhaust steam, the concept of thermal efficiency loses its meaning, because the heat, which transfer heat to the cold source is useful .

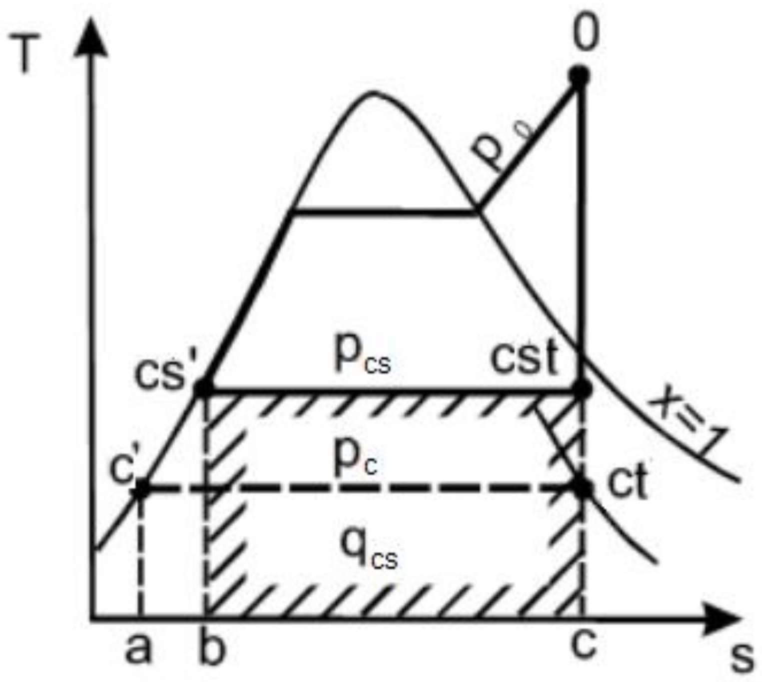
$$\eta_{hu} = \frac{l_{cs} + q_{cs}}{q_1}$$

The coefficient of heat usage

$$sp = \frac{l_{cs}}{q_{cs}}$$

The specific power generation in thermal consumption

The use of district heating



The internal power of the turbine

$$N_i = G_{CS} \cdot (h_0 - h_{cst})$$

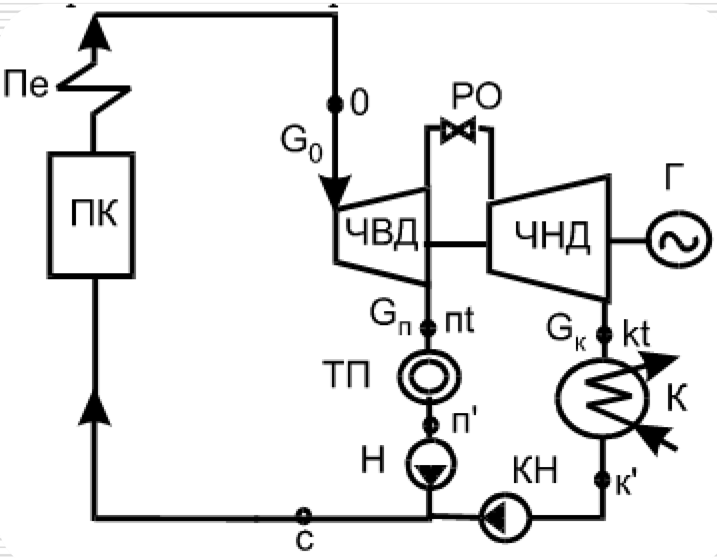
Thermal power

$$Q_{CS} = G_{CS} \cdot (h_0 - h_{cs}^{'})$$

There is hard link because of the proportionality *G*

Using controlled intermediate steam extraction

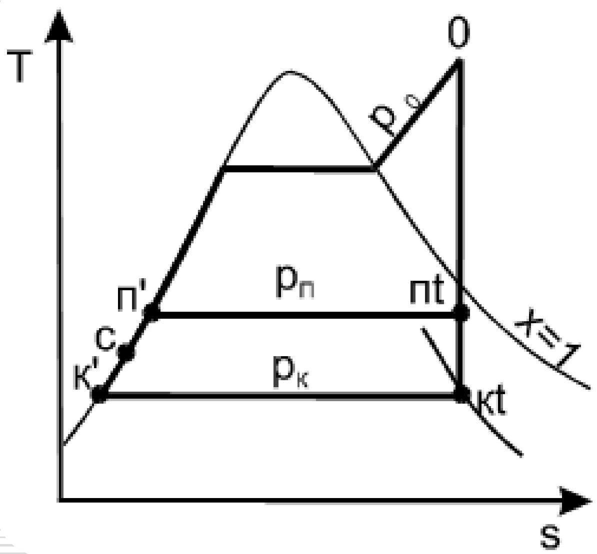
The use of district heating



Cogeneration steam turbine with controlled steam extraction

The turbine consists of two separate parts: the high and low pressure. Steam is expanded in the high pressure part of the turbine to the pressure $p_п$ of controlled steam extraction, which is necessary for the heat consumer.

The use of district heating



0-kt – adiabatic expansion of the steam

0-nt – process in the high pressure part of the turbine

nt-kt – process in the low pressure part of the turbine

nt-n' – extraction of heat to the heat consumer

kt-k' – condensation of the steam in the condenser

k'-c – increasing *h* and *T* when the primary condensate is mixed with the condensate from the consumer

c-0 – heat supply in the working fluid

The use of district heating

The coefficient of heat usage is 60...80% in modern cogeneration plants.

In general, a modern steam turbine installation includes all of the ways to improve the efficiency of the cycles.