2. Methods to improve the thermal efficiency of steam turbines

$$\eta_э = \eta_t \eta_{oi} \eta_м \eta_{эг}$$

A. Thermodynamic methods

aimed to increase $\boldsymbol{\eta_t}$. However, they affect $\boldsymbol{\eta_{oi}}$.

- Increasing the initial parameters
- Reduction of the final pressure
- Resuperheating and moisture separation
- Regenerative feed-water heating

Combined production of electricity and heat

Б. Constructional methods

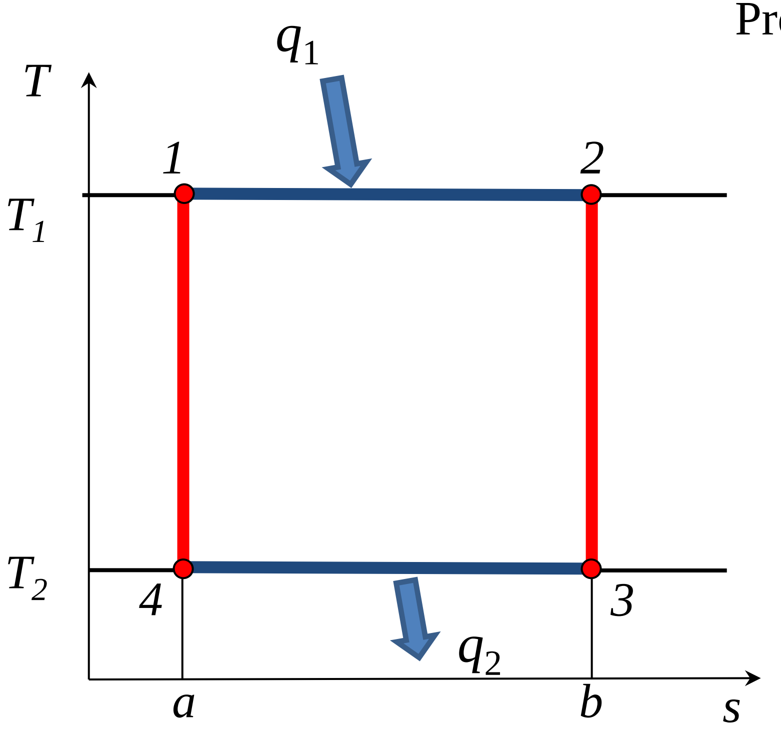
Aimed to increase $\boldsymbol{\eta_{oi}}$, $\boldsymbol{\eta_м}$, $\boldsymbol{\eta_{эг}}$.

2.1. Methods of thermodynamic analysis of the cycle

A) Carnot Cycle

Nicolas Léonard Sadi Carnot (1796-1832)

The specified temperature range for the working medium of the cycle: T_1 and T_2



Processes: *1-2* – heat supply:

$$q_1 = \text{area: } a12ba = \int_1^2 T ds = T_1 (s_b - s_a)$$

3-4 – heat removal:

$$q_2 = \text{area: } a43ba = \int_3^4 T ds = T_2 (s_b - s_a)$$

4-1 – adiabatic compression;

2-3 – adiabatic expansion.

EF of the Carnot Cycle:

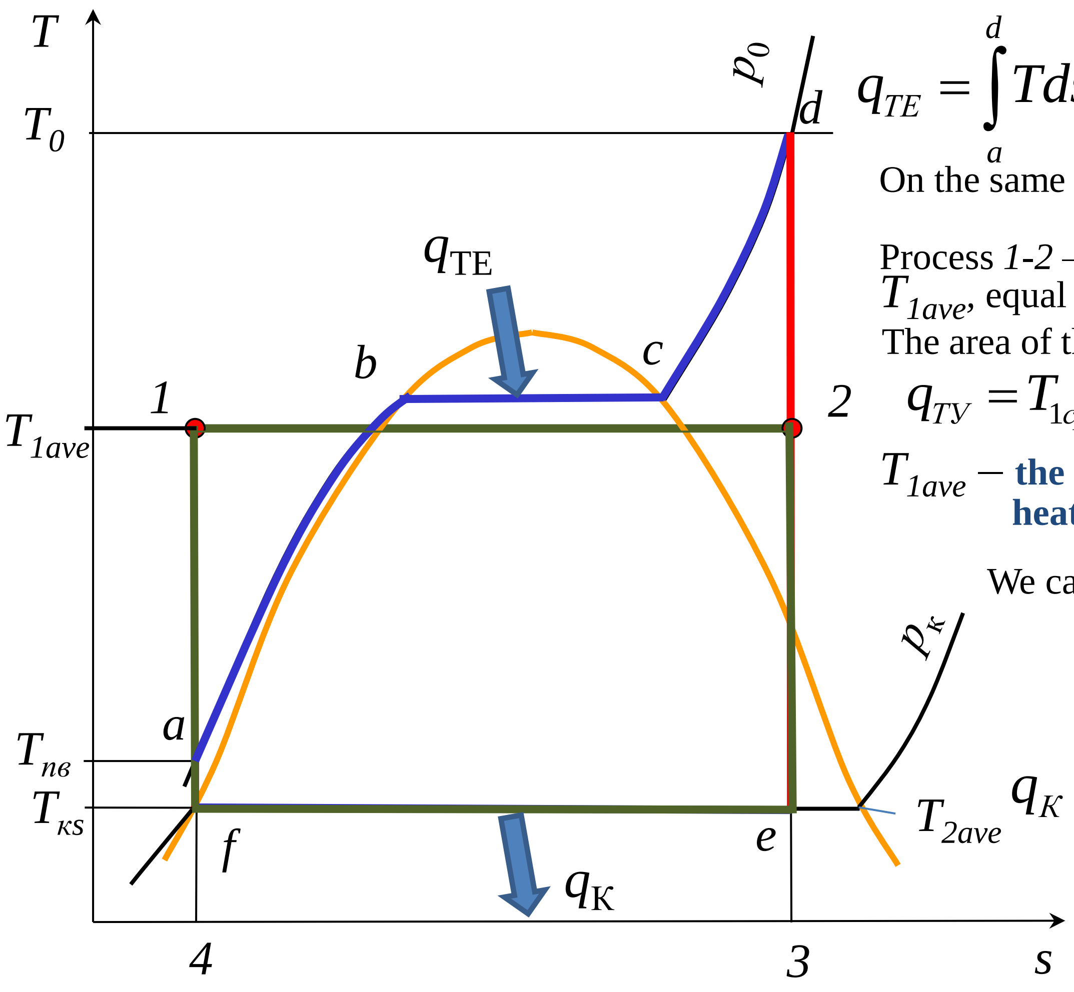
$$\eta_t^{ц.К} = \frac{q_1 - q_2}{q_1} = 1 - \frac{q_2}{q_1} = 1 - \frac{T_2 (s_b - s_a)}{T_1 (s_b - s_a)}$$

$$\eta_t^{ц.К} = 1 - \frac{T_2}{T_1}$$

B) Real medium cycle

(consider the cycle of the steam turbine equipment)

The specified operating temperature range for the working medium (H_2O): $T_{пв}$ and $T_{кs}$



Processes: ***abcd* – heat supply:**

$$q_{TE} = \int_a^d Tds = \text{area: } 4abcd34 = h_0 - h_{пв} = пл.41234$$

On the same basis, take (3-4) rectangle of the area equal q_{TE}

Process *1-2* – isothermal heat supply process at some temperature T_{1ave}, equal to q_{TE}.

The area of the rectangle is equal to:

$$q_{TУ} = T_{1cp}\left(s_3 - s_4\right) \quad *$$

T_{1ave} – **the average temperature in heat supply process *abcd*, heat supply in the real medium cycle**.

We can determine:

$$T_{1cp} = \frac{h_0 - h_{пв}}{s_2 - s_1}$$

***e-f* – heat removal:**

$$q_K = \int_e^f Tds = пл.1fe21 = T_{2cp}\left(s_2 - s_1\right) **$$

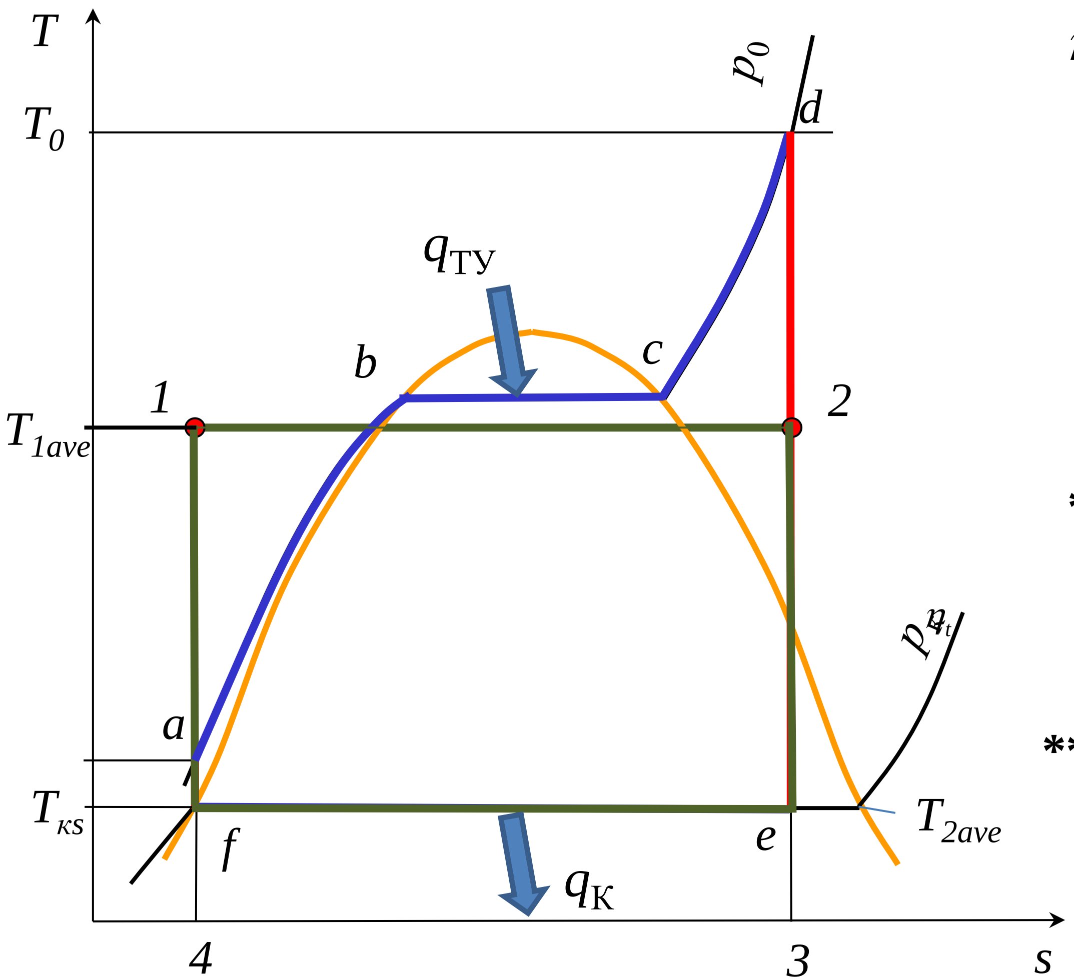
T_{2ave} – **average temperature in the heat supply process *ef*, in heat removal in real medium cycle**.

$$T_{2cp} = \frac{h_{кt} - h'_к}{s_2 - s_1}$$

$$\eta_t = 1 - \frac{q_K}{q_{TE}} = 1 - \frac{T_{2cp}}{T_{1cp}}$$

***d-e* – adiabatic expansion**

***f-a* – adiabatic compression**



$$\eta_t = 1 - \frac{T_{2cp}}{T_{1cp}}$$

* Cycle EF does not depend on the properties of the working medium and is determined only by the ratio of average temperatures of heat removal and heat supply.

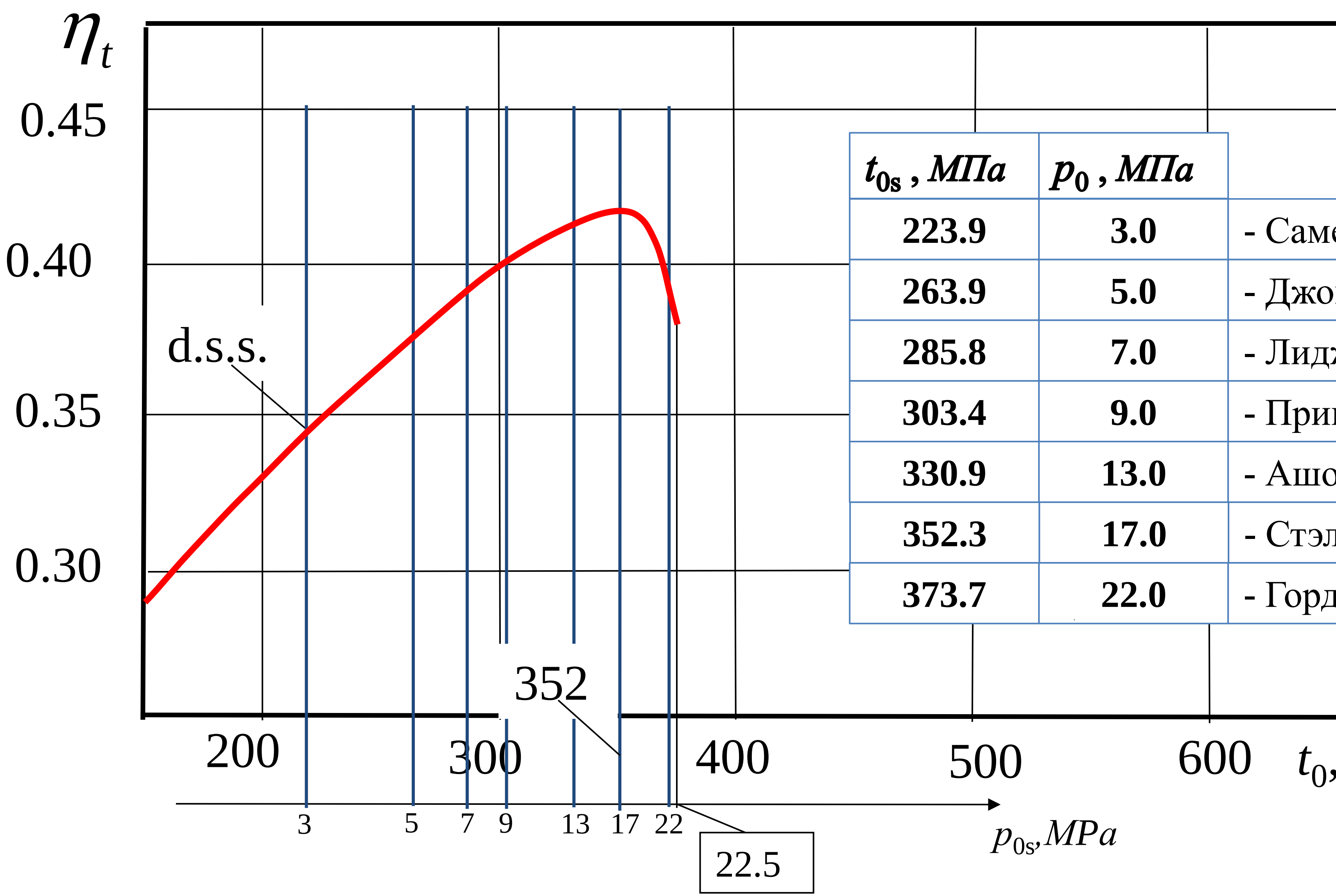
** the average temperature of heat supply (removal) depends on the medium properties

*** in a given temperature range, EF of the Carnot cycle is the largest

2.2. Impact of initial parameters on EF of STE

A) EF of an ideal cycle

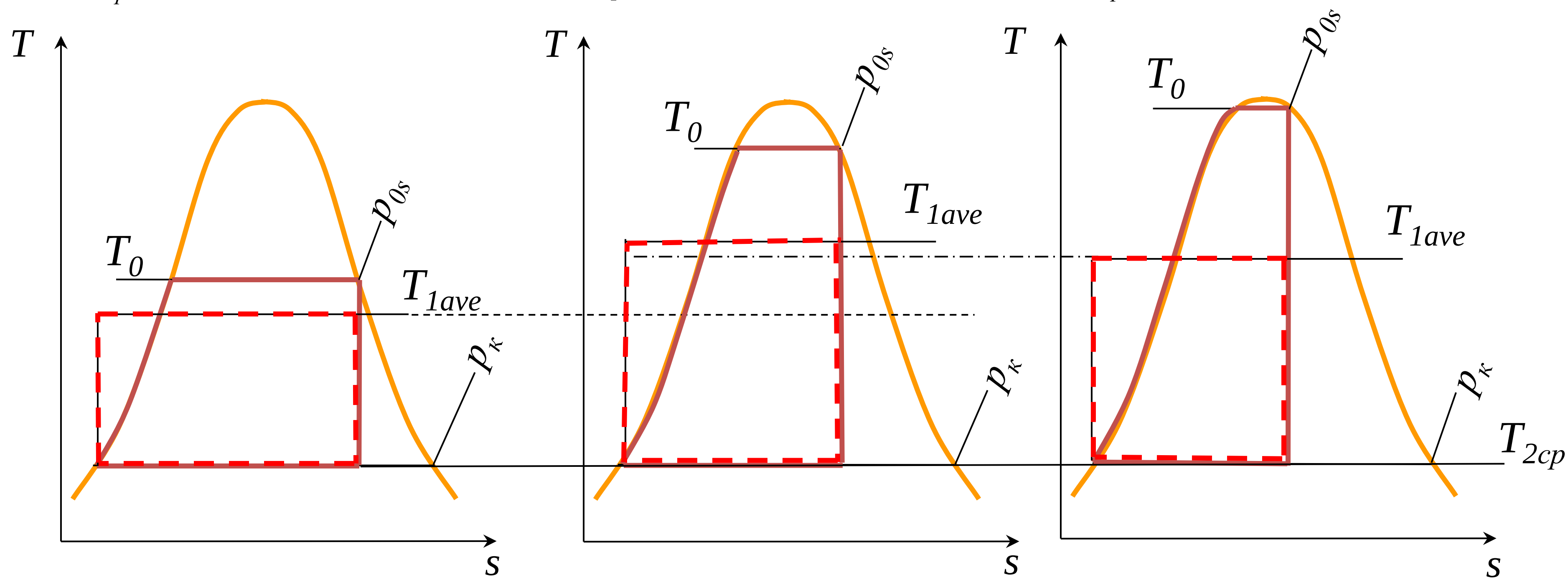
- ***cycle of dry saturated steam***



t_{0s} , МПа	p_0 , МПа	
223.9	3.0	- Самех
263.9	5.0	- Джошуа
285.8	7.0	- Лиджу
303.4	9.0	- Принсвилл
330.9	13.0	- Ашок
352.3	17.0	- Стэлла
373.7	22.0	- Гордон

I $t_{0s} = 210^0 C\left(p_{0s} = 1{,}9 МПа\right)$ **II** $t_{0s} = 350^0 C\left(p_{0s} = 16{,}5 МПа\right)$ **III** $t_{0s} = 370^0 C\left(p_{0s} = 21{,}05 МПа\right)$

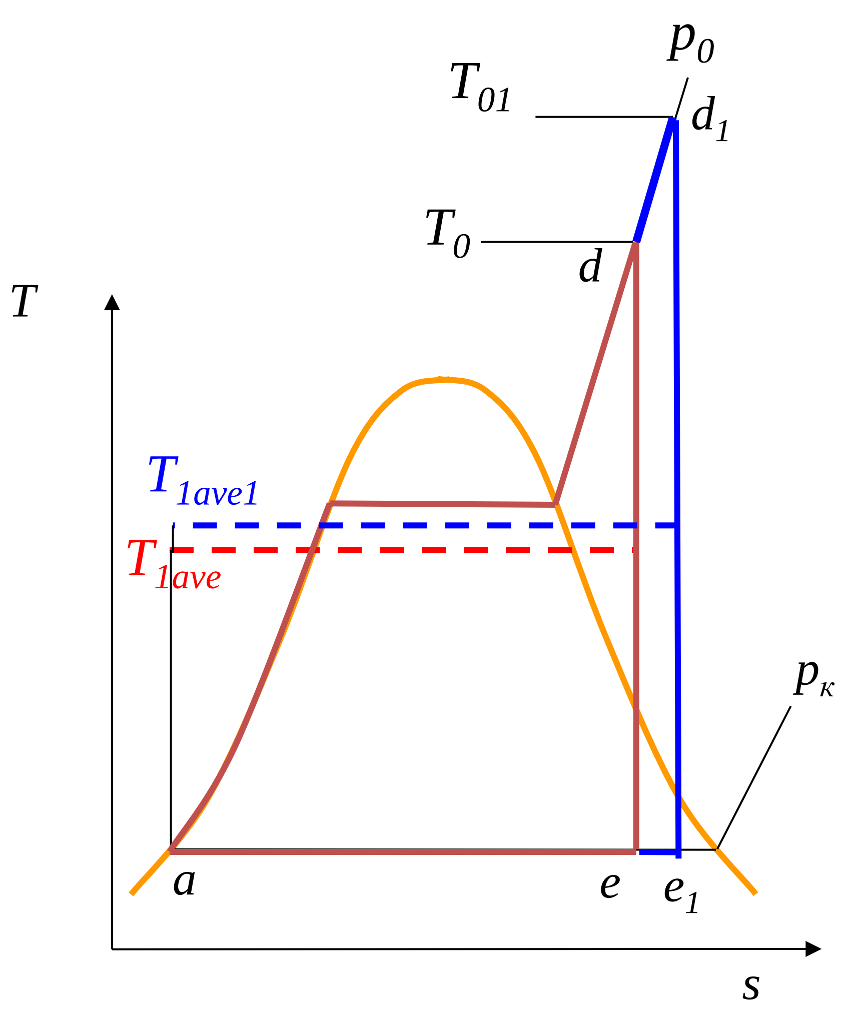
$T_{1cp} = 450{,}9К$ $T_{1cp} = 510{,}0К$ $T_{1cp} = 505{,}4К$



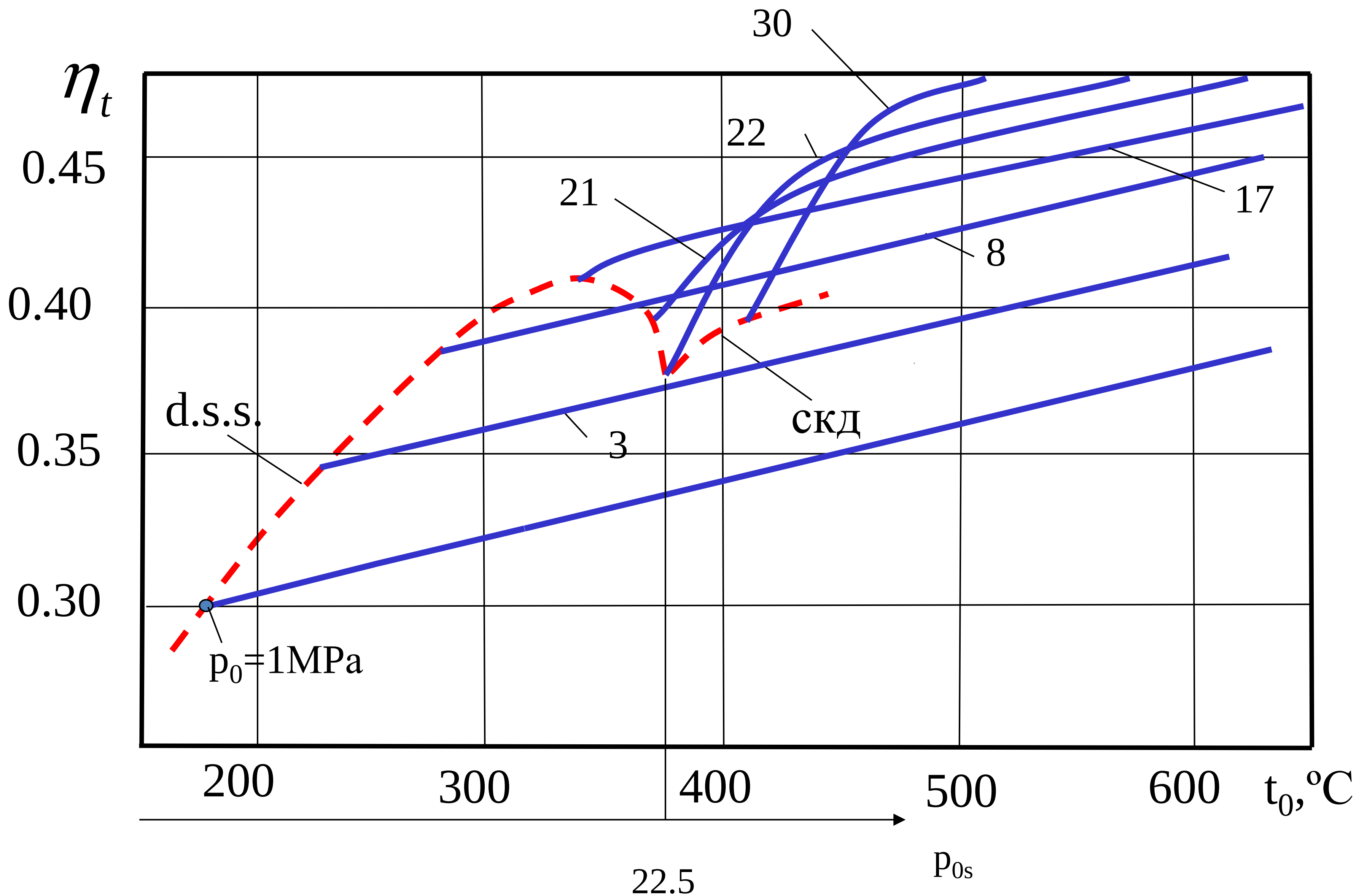
$\eta_t^I < \eta_t^{II} > \eta_t^{III}$ since $T_{1cp}^I < T_{1cp}^{II} > T_{1cp}^{III}$

▪ ***cycle of superheated steam*** $[\eta_t=f(t_0, p_0)]$

a) impact of initial temperature (at $p_0=const$)

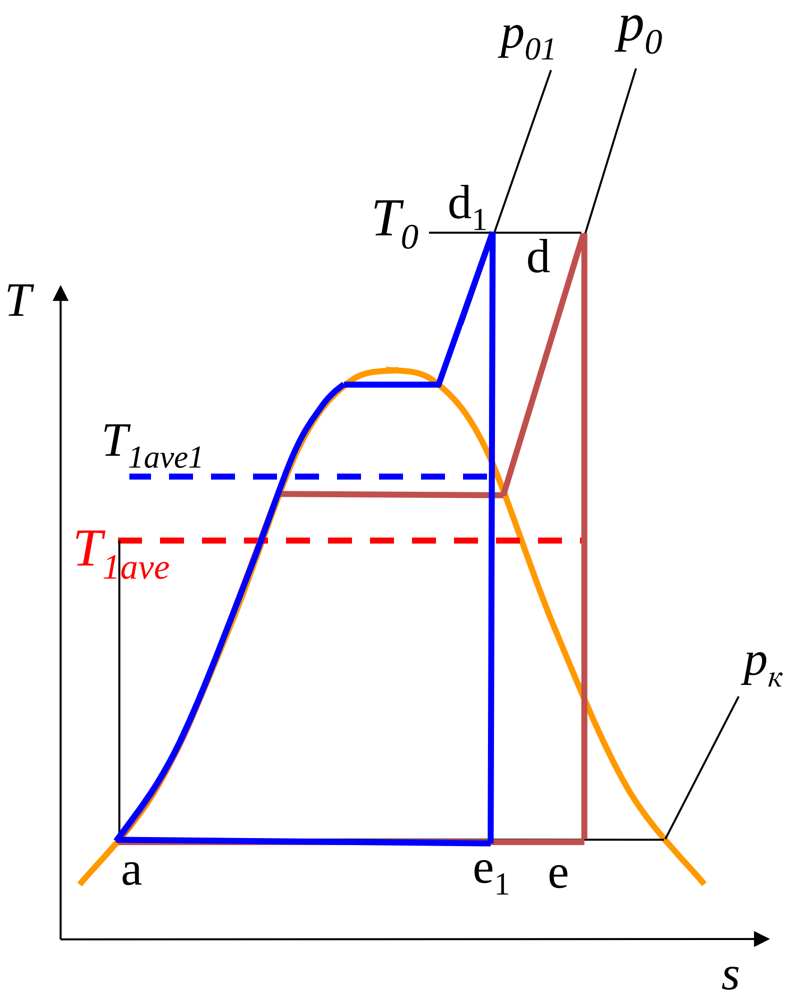


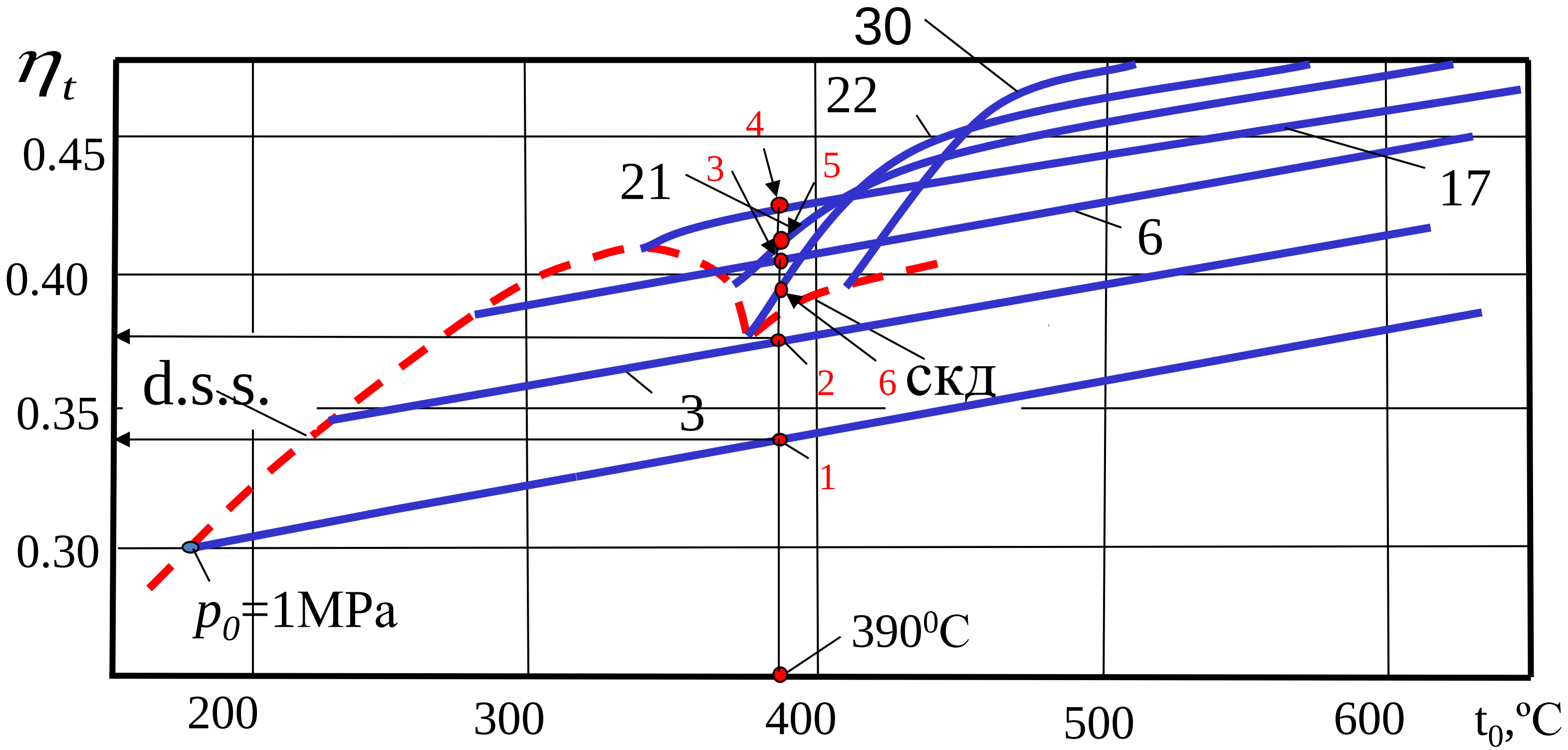
Increased initial temperature at constant pressure always results in increased thermal EF



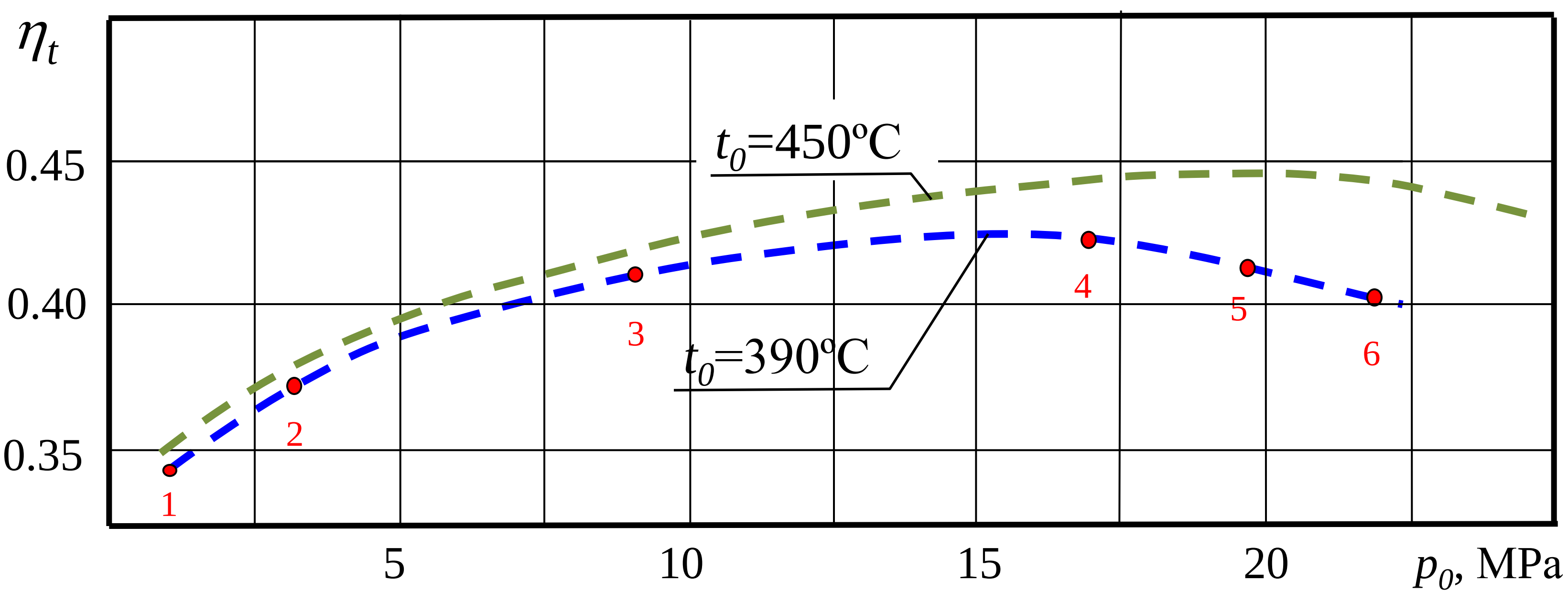
30
η_t
22
0.45
21
17
8
0.40
d.s.s.
3
скд
0.35
0.30
p_0=1MPa
200
300
400
500
600
t_0,ºC
p_{0s}
22.5

b) impact of initial pressure (at t_0=*const*)

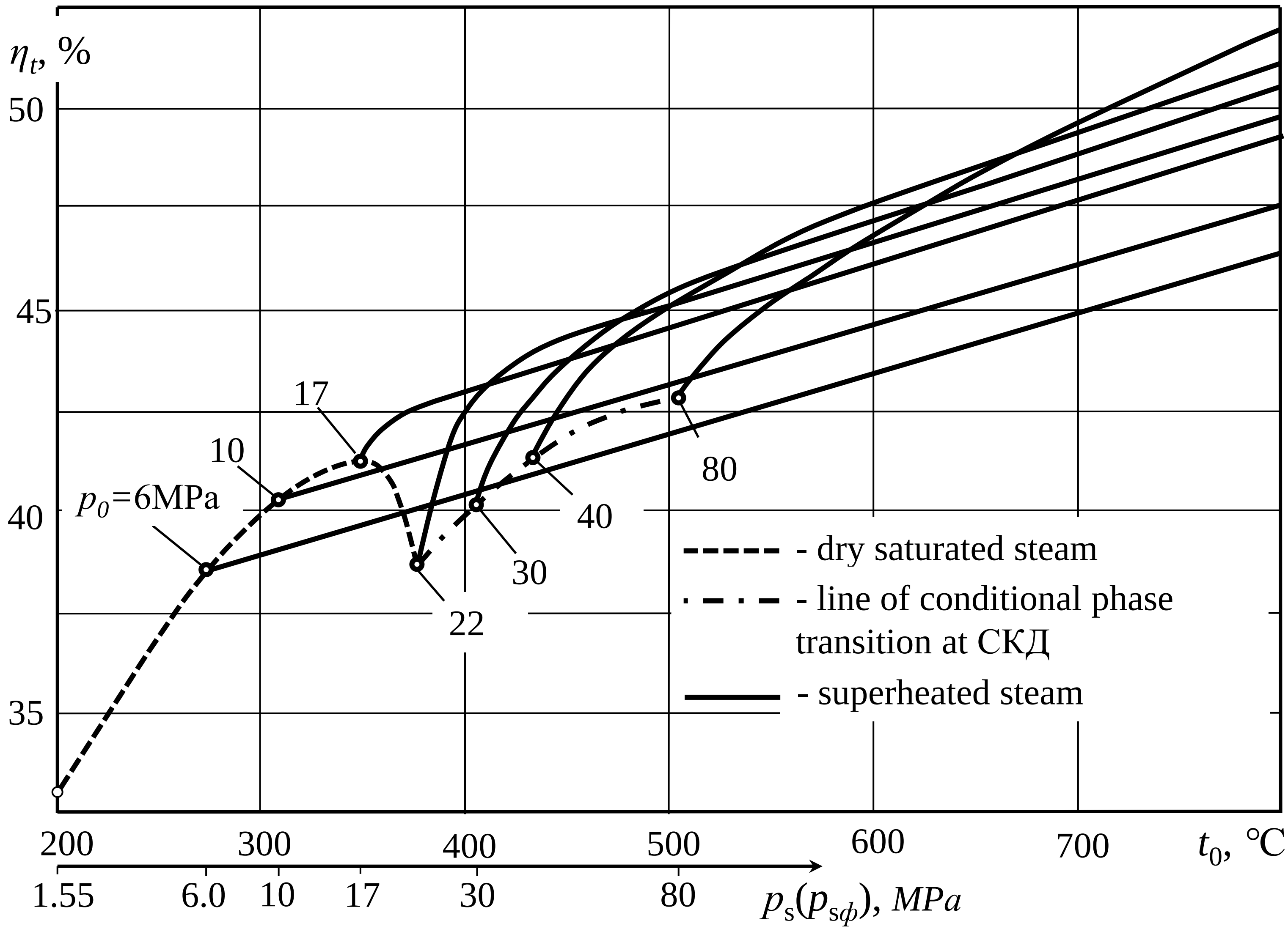




ηt
30
22
21
4
3
5
17
6
0.45
0.40
0.35
0.30
скд
2
6
3
d.s.s.
1
p0=1MPa
390⁰C
200
300
400
500
600
t0,ºC



ηt
0.45
0.40
0.35
t0=450ºC
t0=390ºC
1
2
3
4
5
6
5
10
15
20
p0, MPa



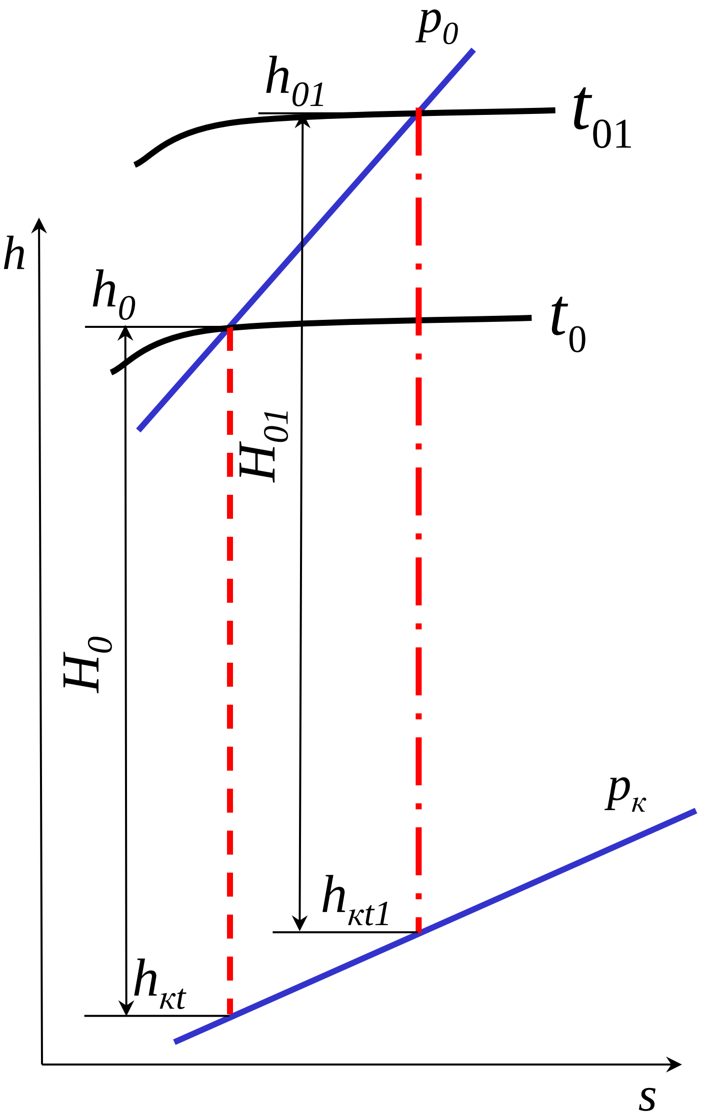
Dependence of thermal EF (η_t) on initial temperature (t_0) at different initial pressures (p_0).

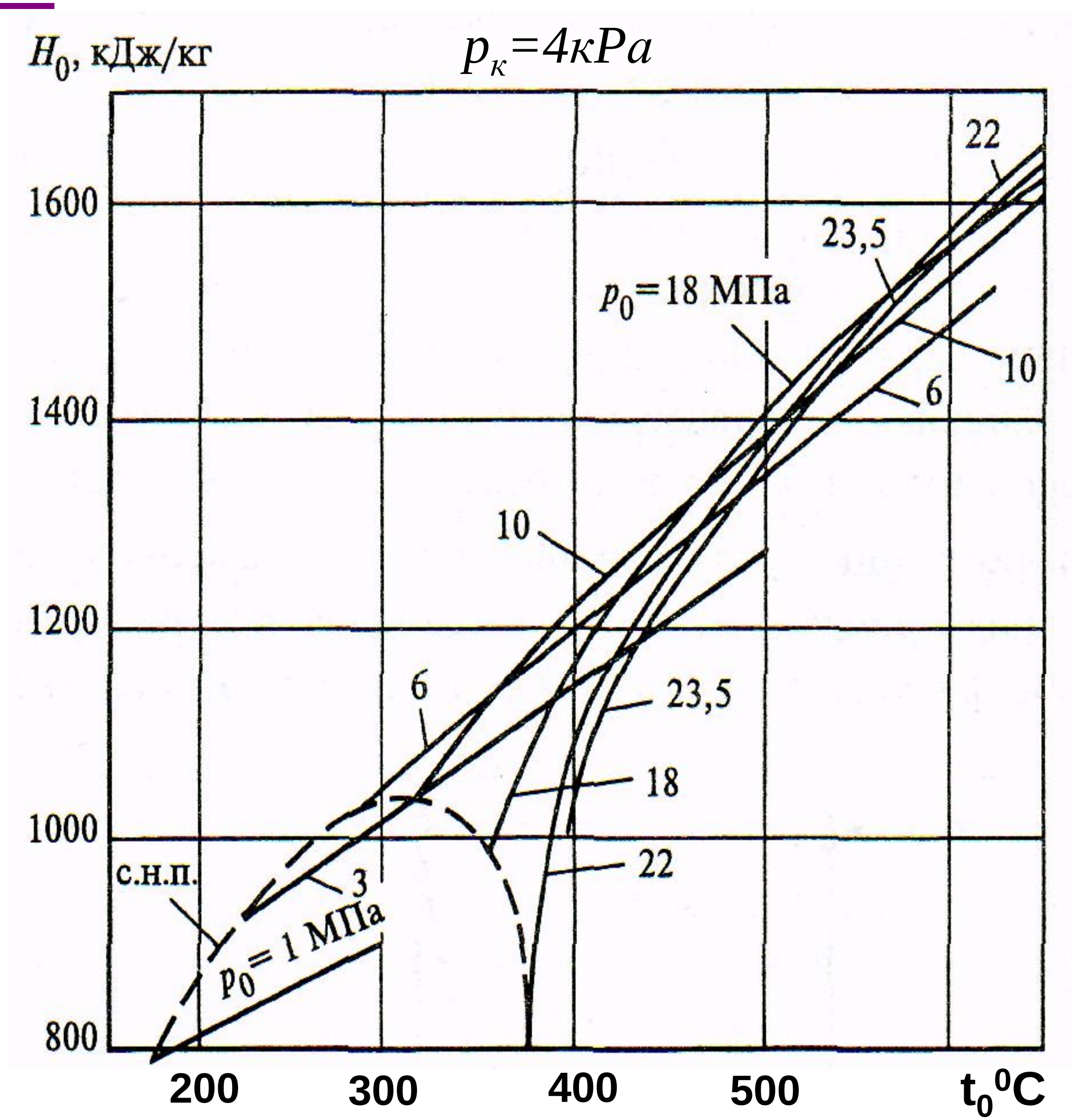
$p_s(p_{s\phi})$ – saturation pressure (at supercritical pressure)

B) Impact of initial parameters on available heat drop of the turbine

$H_0 = h_0 - h_{\kappa t}$

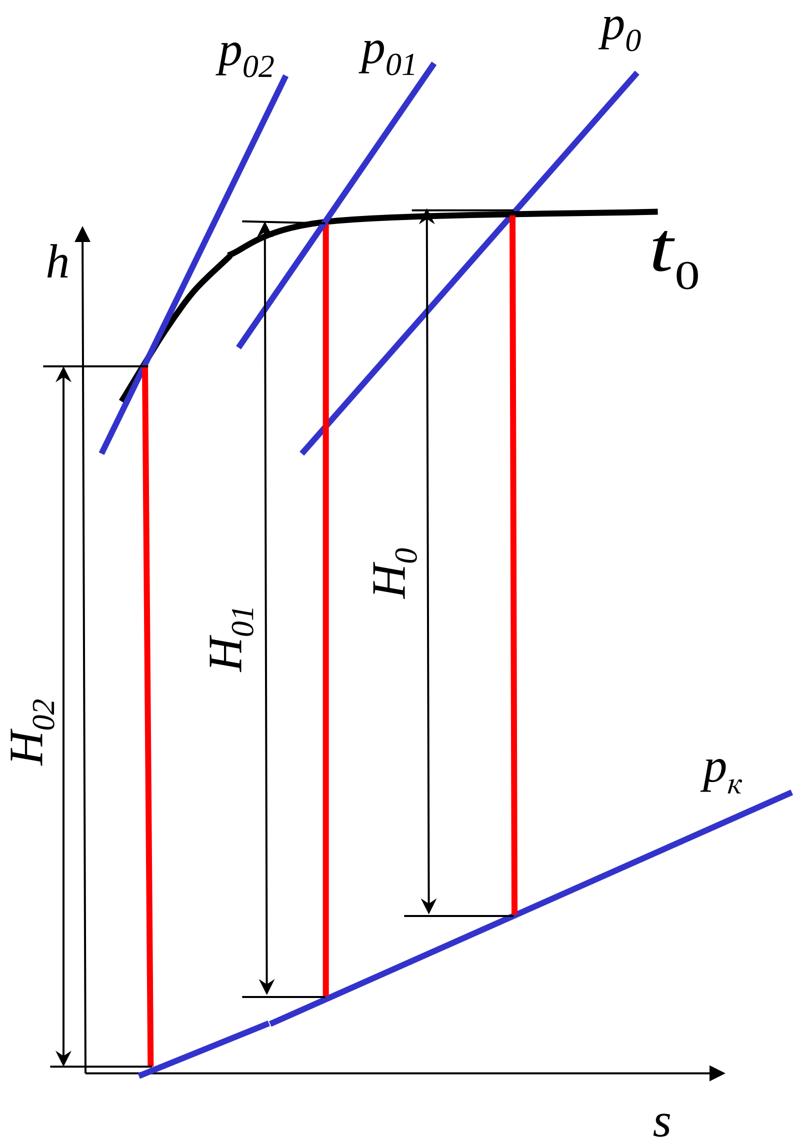
- ***impact of initial temperature***

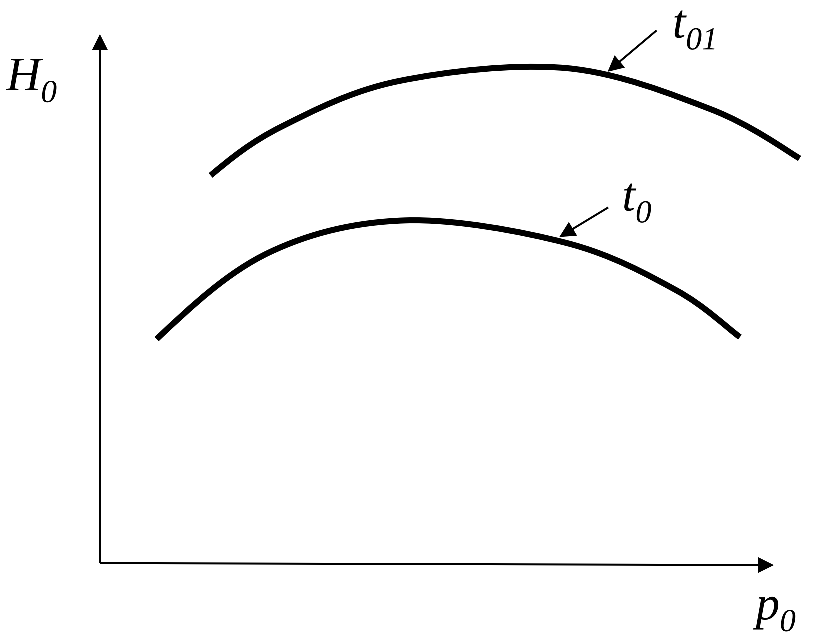




$$H_{01} > H_0$$

- ***impact of initial pressure***





C) Impact of initial parameters on the final degree of dryness

impact of initial parameters on the turbine **efficiency** (on the internal relative EF of the turbine η_{oi}) and **reliability** of the turbine is related to the dependence of the final dryness of steam on initial parameters:

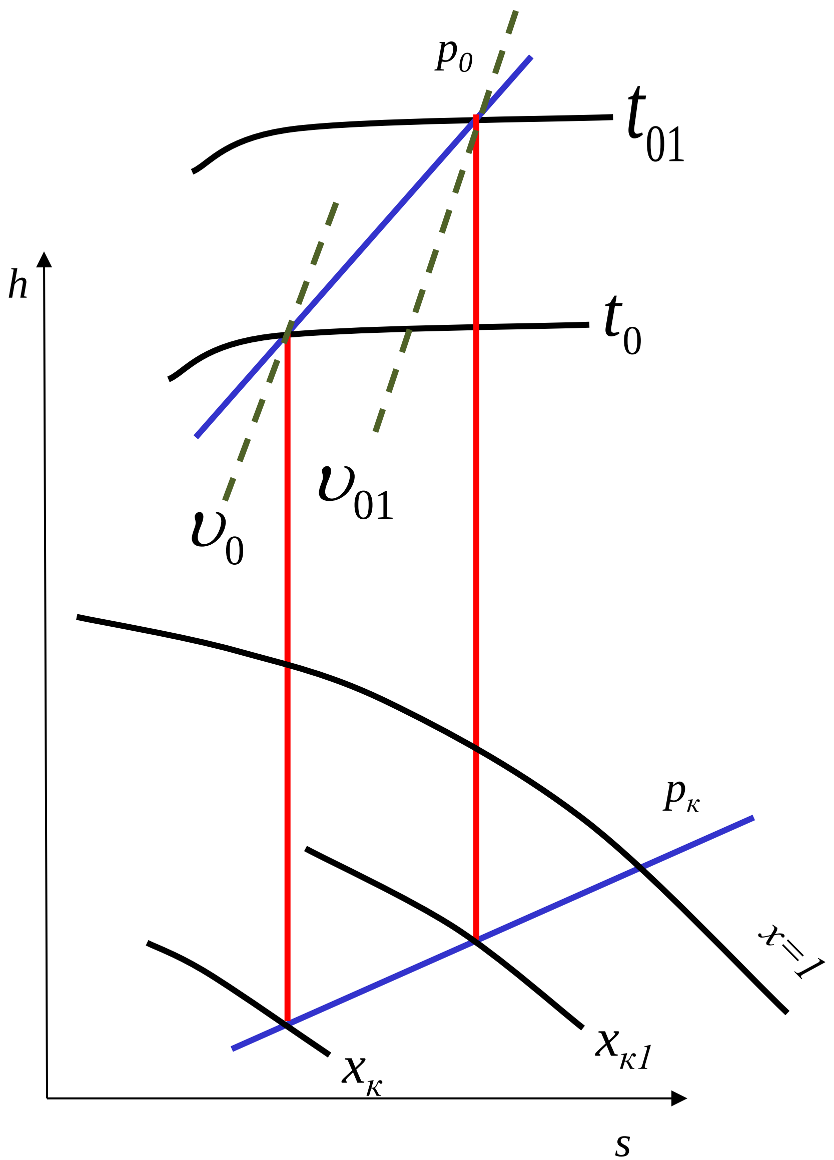
1) depends on the amount of humidity as the energy conversion efficiency (the smaller ***x*,** the smaller the η_{oi})

2) erosive wear of rotor blades depends on the amount of humidity

Erosion of rotor blades is the process of destruction of the surface under the impact of moisture particles

There is a concept of permissible final moisture, i.e. moisture at which the erosive wear of the blades is within an allowable level

- ***impact of initial temperature***



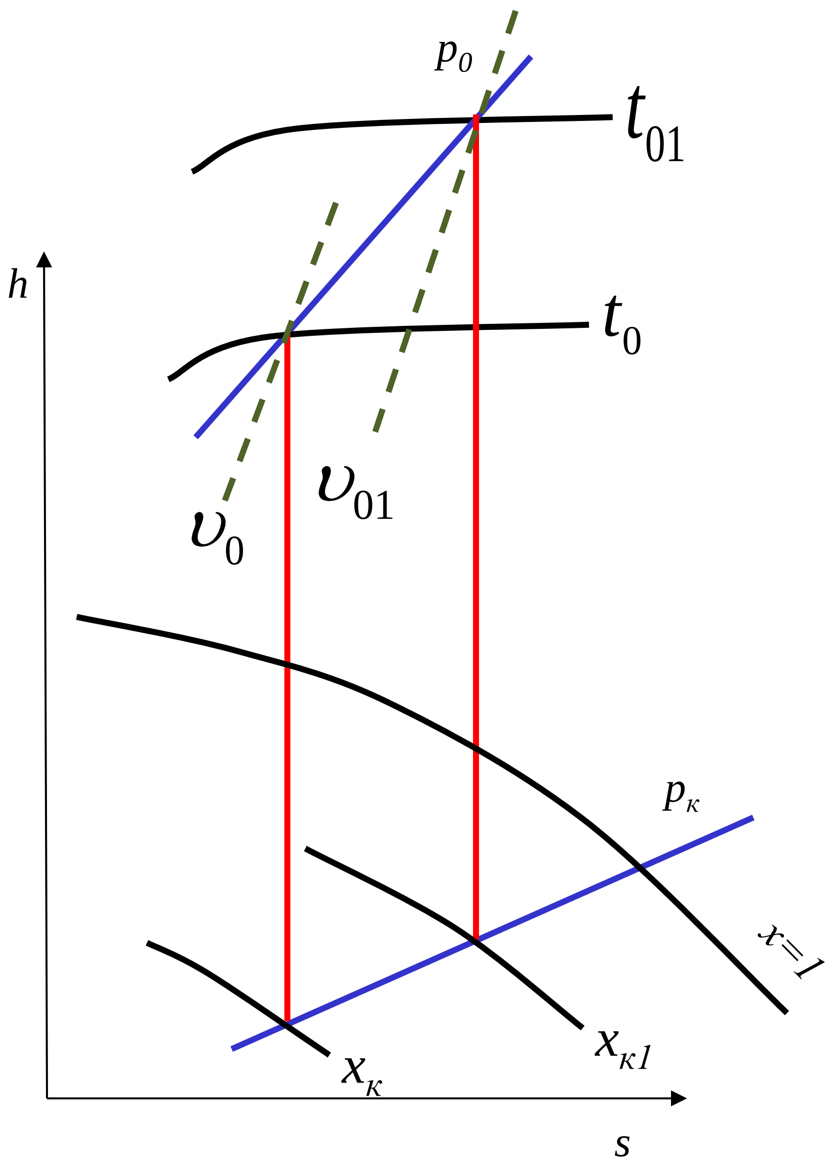
$$t_0 \uparrow \Rightarrow \upsilon_0 \uparrow$$

$$t_0 \uparrow \Rightarrow x_\kappa \uparrow \quad (y_\kappa \downarrow)$$

$$y = 1 - x$$

$$x = \frac{m_\Pi}{m_\Pi + m_B}$$

- ***impact of initial temperature***



$$t_0 \uparrow \Rightarrow x_\kappa \uparrow \quad (y_\kappa \downarrow)$$

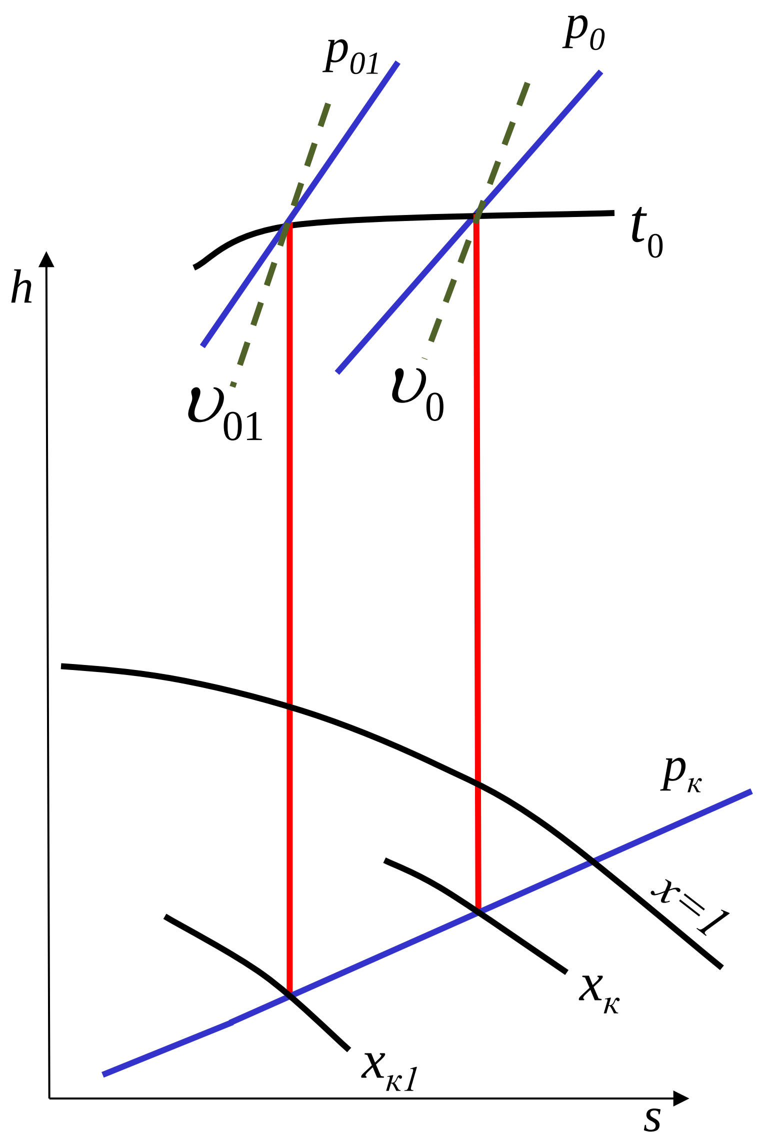
Degree of moisture:

$$y = 1 - x$$

Degree of dryness:

$$x = \frac{m_\Pi}{m_\Pi + m_B}$$

- ***impact of initial pressure***



$$p_0 \uparrow \Rightarrow x_к \uparrow$$

1.2.2. impact of initial parameters on EF of the steam turbine equipment (CONCLUSIONS)

A. Increased initial temperature:

- causes increase in η_t
- effects η_{oi}

(since: - the specific volume of steam at the beginning of expansion grows, hence, the height of the first stage turbine blades increases
- the final degree of moisture decreases, hence, moisture-related losses in the last stages of the turbine are reduced)

+

However: There is a limit on the initial temperature in terms of mechano-caloric properties of advanced materials and their cost.

A. Increased initial pressure:

- has maximum value η_t
- has a negative effect on η_{oi}

(since: - the specific volume of steam at the beginning of expansion grows, hence, the height of the first stage turbine blades decreases
- the final degree of moisture grows, hence, moisture-related losses in the last stages of the turbine increase)

+?

Considering the current state and techniques to compensate for the negative impact:

- at available initial temperatures, modern energy cannot provide the initial pressure to ensure maximum η_t
- the negative effect of the reduced initial volume can be compensated by joint increase of p_0 and t_0, and increase of the turbine power, and hence increase of the steam flow in the turbine and volumetric flow
- the negative effect caused by increase in the final moisture can be eliminated through **reheating stage**