TOMSK POLYTECHNIC UNIVERSITY

REGENERATIVE HEATING OF THE FEED WATER (RHFW)

MAIN FEATURES

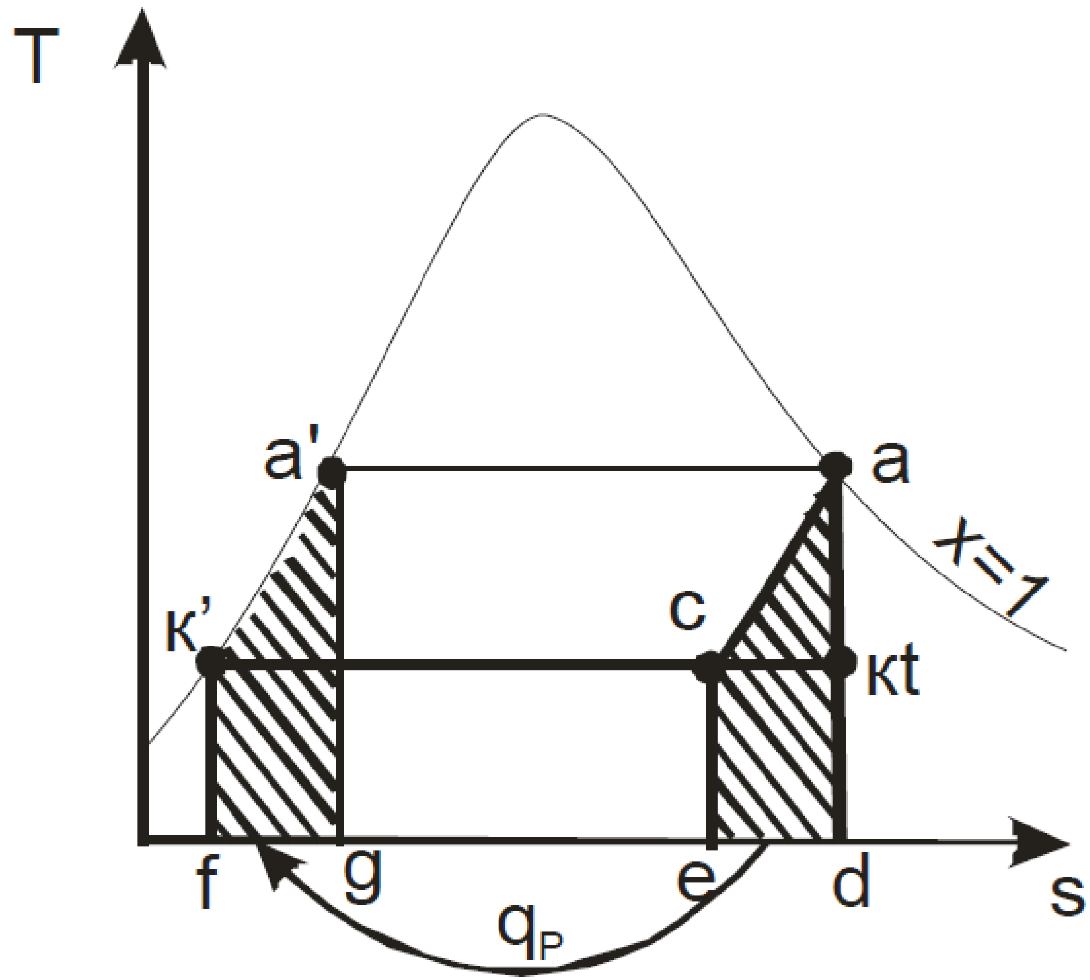
- Theoretical cycle with heat regeneration
- Real cycle with heat regeneration
- Effect of RHFW on the efficiency of NPP
- Distribution of regenerative bleed into turbine
- Steam and drainage cooling

EFFECT OF FEED WATER TEMPERATURE ON EFFICIENCY

- To improve efficiency of NPP the average temperature of heat supplied to cycle should be increased. When ability to increase temperature on the inlet of steam turbine is depleted this could be reached by increasing the temperature of the feed water on the inlet of steam generator.

- The most efficient method to increase temperature on the inlet of steam generator is application of regenerative heating of feed water.

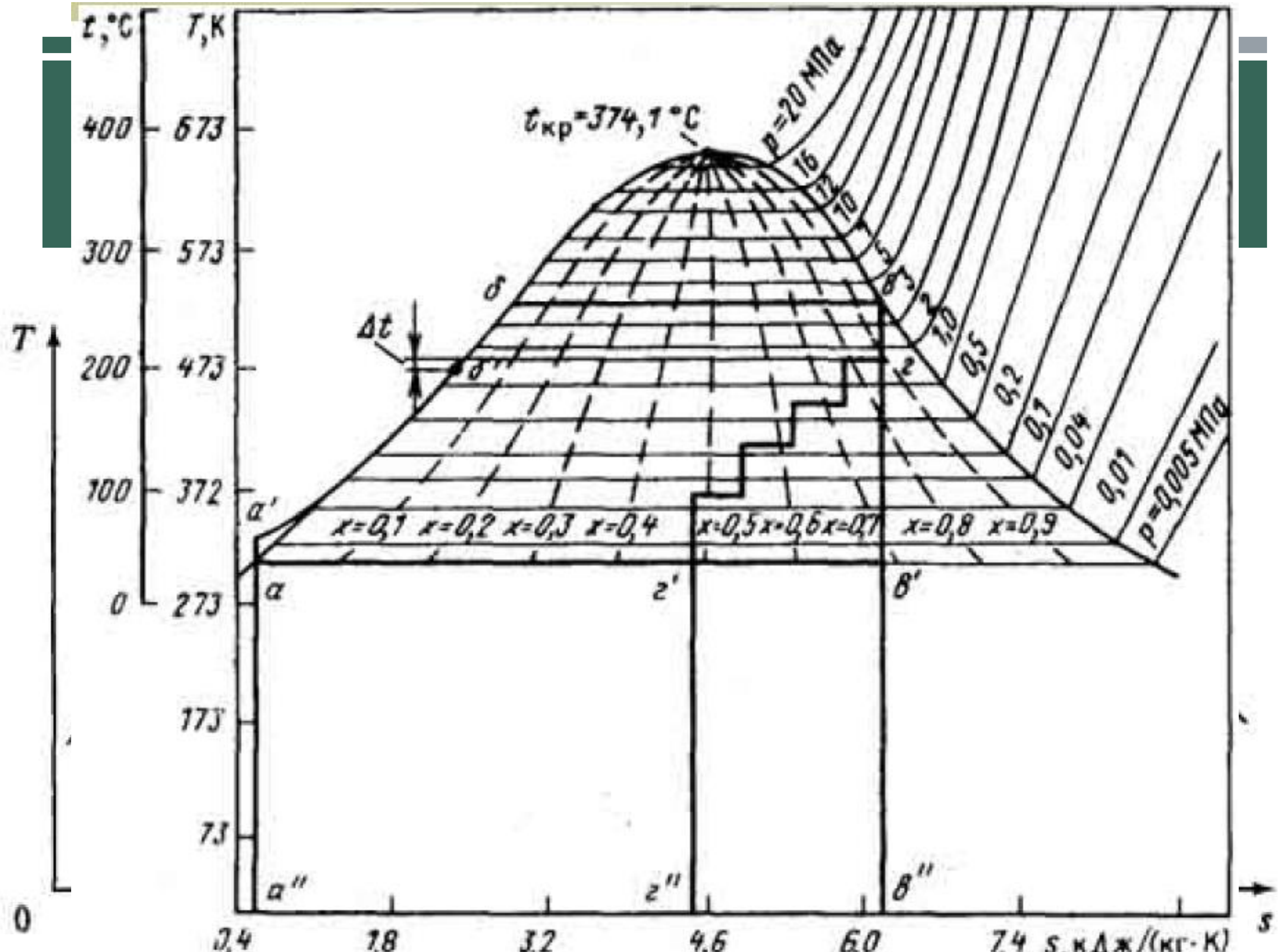
REGENERATIVE HEATING OF THE FEED WATER (RHFW)



Regenerative heating of the feed water (RHFW) – application of heat of working fluid, which have conducted mechanical work in turbine, on the different part of the cycle.

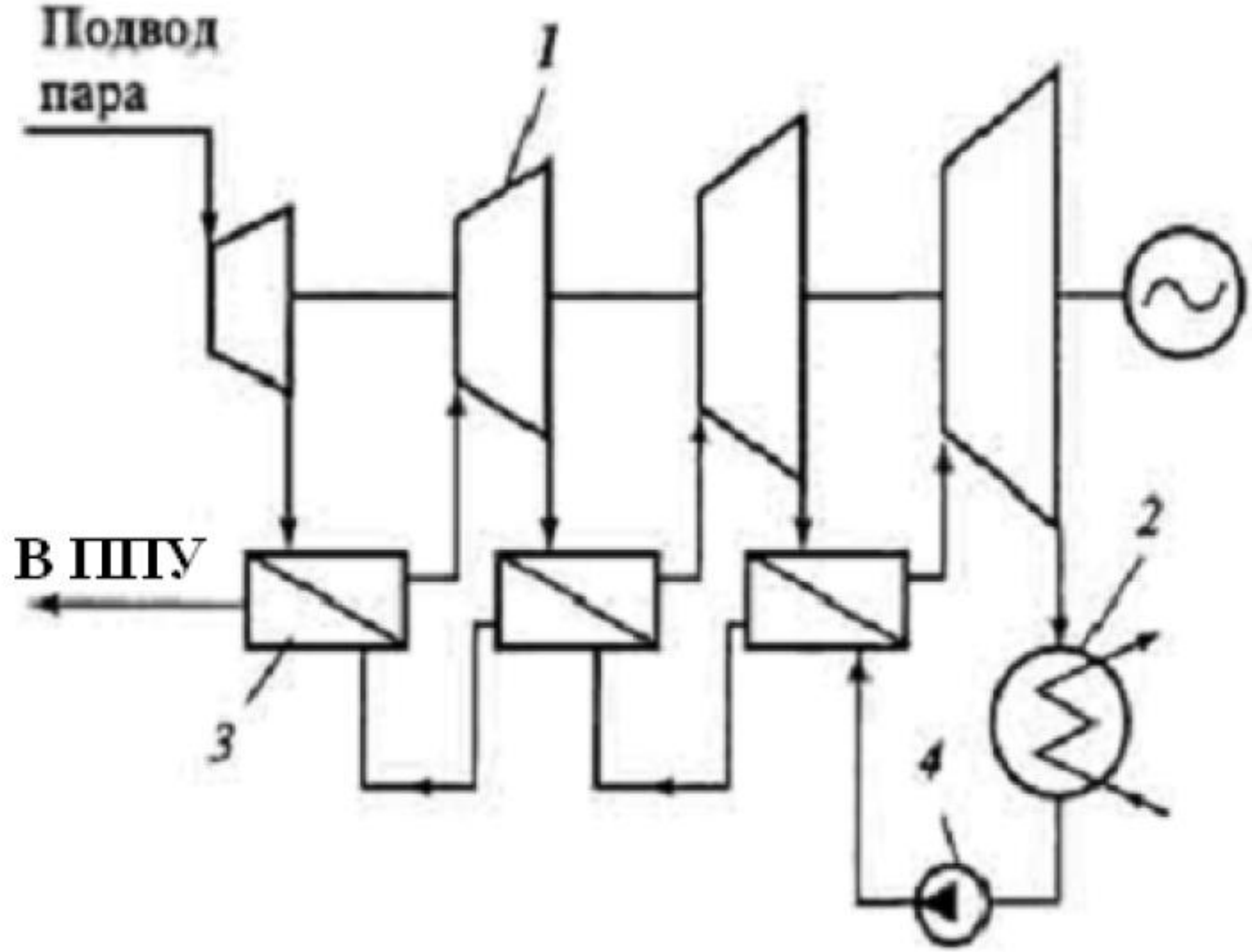
Effect of RHFW:

- Decreasing of the thermodynamic irreversibility of heating on the line k'-a'
- Decreasing of heat losses into cold source (condenser)



t, °C
T, K
400
673
300
573
200
473
100
372
0
273
173
73
T
0
s
$t_{кр}$ = 374,1 °C
p = 20 МПа
16
12
10
5
3
2
1,0
0,5
0,2
0,1
0,04
0,01
p = 0,005 МПа
Δt
б
б''
б'
г
x = 0,1
x = 0,2
x = 0,3
x = 0,4
x = 0,5
x = 0,6
x = 0,7
x = 0,8
x = 0,9
a'
a
a''
г'
г''
в'
в''
0,4
1,8
3,2
4,6
6,0
7,4
s, кДж/(кг · К)

SCHEME OF THEORETICAL CYCLE WITH REGENERATIVE HEATING



FINITE THEORETICAL CYCLE WITH REGENERATIVE HEATING

Finite theoretical regenerative cycle:

- Infinite amount of regenerative bleeds;
- Infinitively low heat drops at each stage.

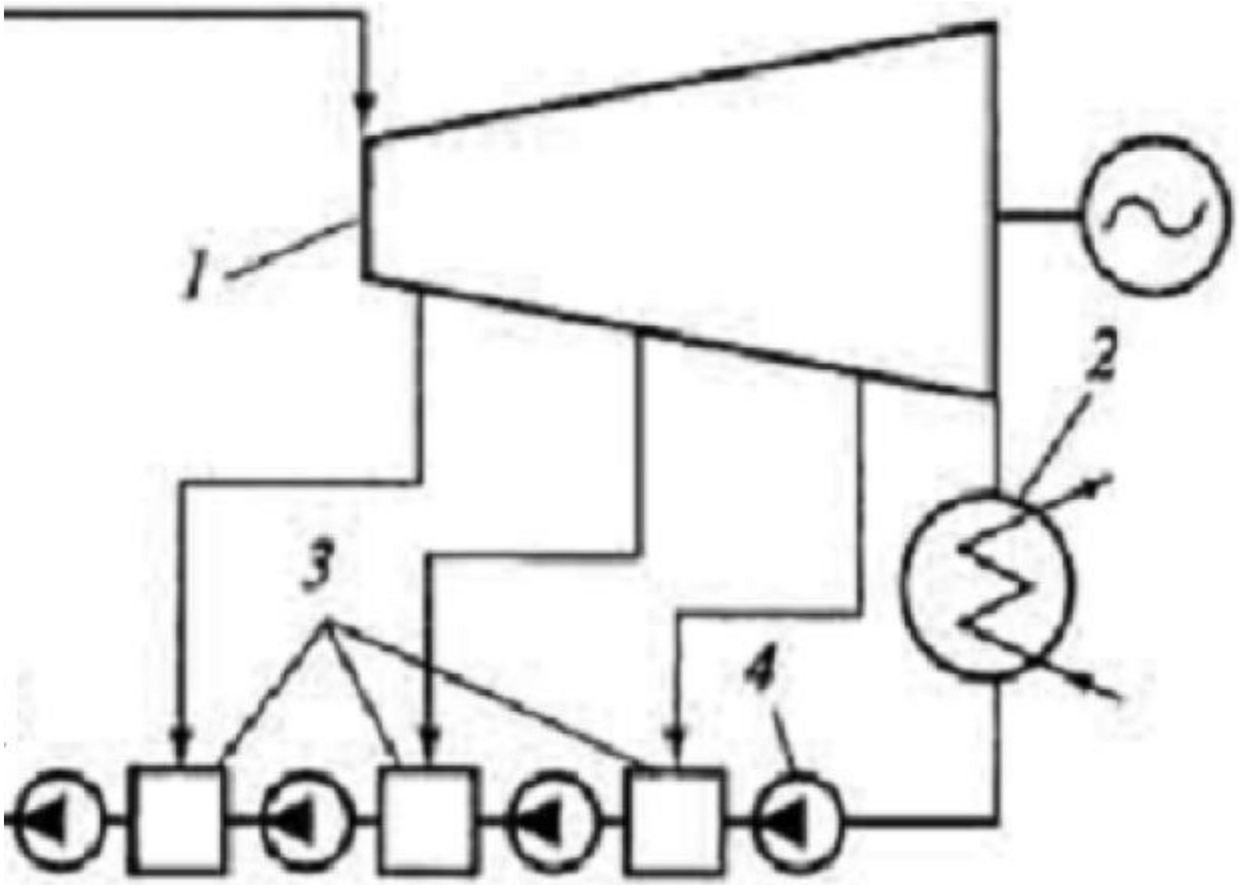
Impossibility of theoretical regenerative cycle:

- Unacceptable humidity in the end of expansion process;
- Large dimensions of heaters, bleed cross-section area and pipelines;
- High pressure losses.

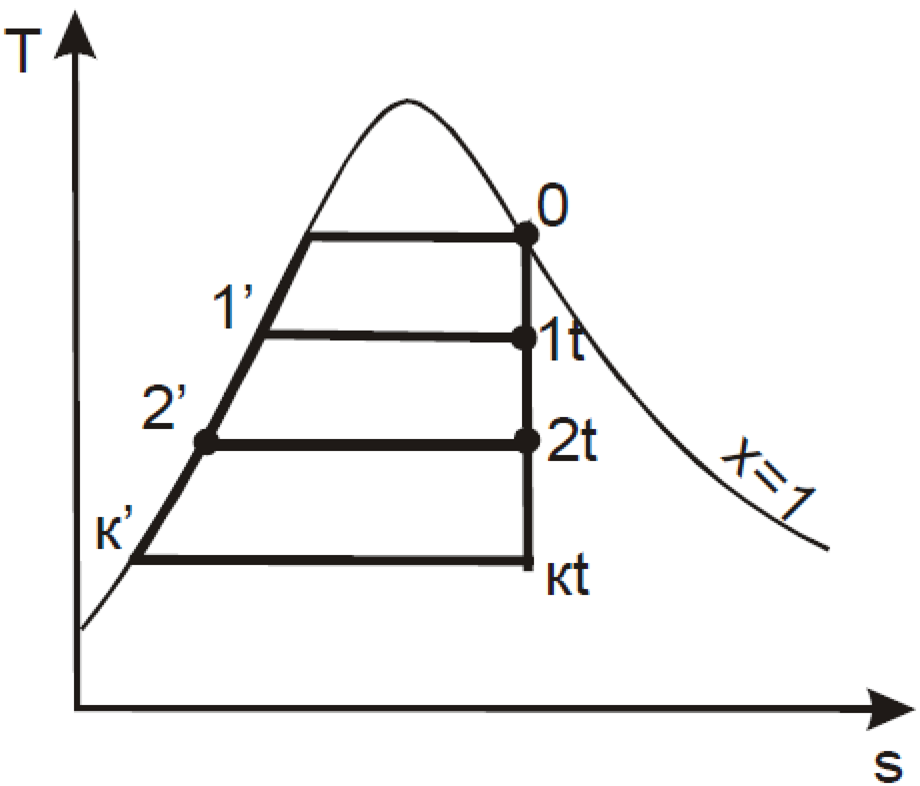
THREE STAGE RHFW OF THE OPEN TYPE

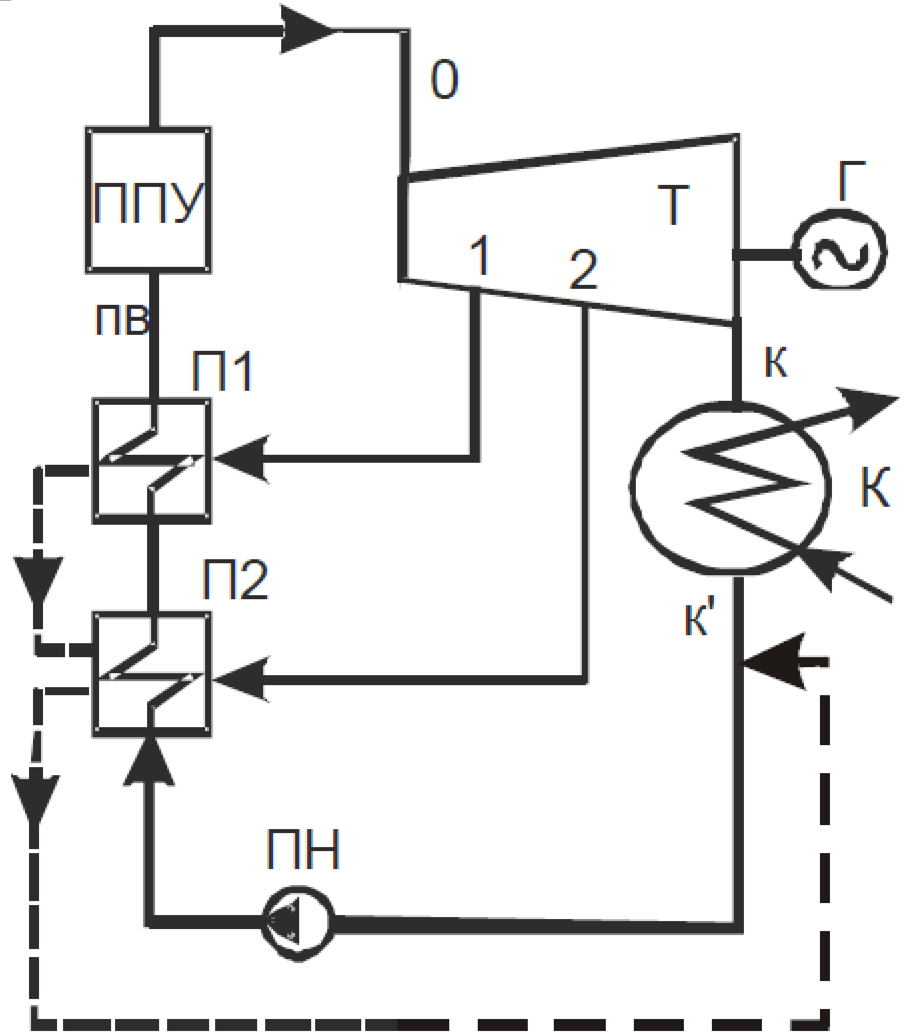
One stage of RHFW includes:

- Steam bleed;
- Heater;
- Steam pipeline;
- Pump (optional);
- Drain line (optional).

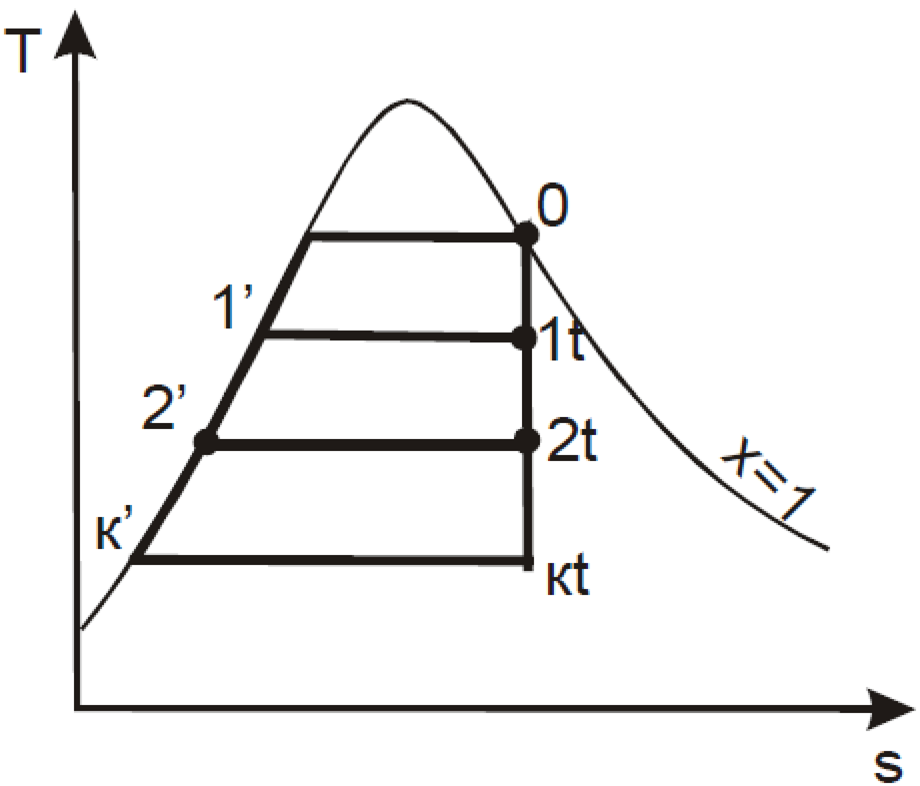


SCHEME AND CYCLE OF TWO STAGE RHFW OF THE CLOSED TYPE





WORK OF TURBINE IN SCHEME WITH TWO STAGE RHFW



Theoretical work:

$l_t = l_I + l_{II} + l_k = (h_0 - h_{It}) + (1 - \alpha_1)(h_{It} - h_{2t}) + (1 - \alpha_1 - \alpha_2)(h_{2t} - h_{kt}) = h_0 - \alpha_1 h_{It} - \alpha_2 h_{2t} - \alpha_k h_{kt}$

Real work:

$l_t = l_I + l_{II} + l_k = (h_0 - h_I) + (1 - \alpha_1)(h_I - h_2) + (1 - \alpha_1 - \alpha_2)(h_2 - h_k) = h_0 - \alpha_1 h_I - \alpha_2 h_2 - \alpha_k h_k$

PARAMETERS OF NPP IN SCHEME WITH N-STAGED RHFW

- Effective heat drop of turbine with nth stages:

$$l_i^p = H_i^p = h_0 - \sum_{j=1}^{n} \alpha_j h_j - \alpha_k h_k$$

- By substituting $\alpha_k = 1 - \sum_{j=1}^{n} \alpha_j$ we get:

$$H_i^p = h_0 - h_k - \sum_{j=1}^{n} \alpha_j \left(h_j - h_k \right)$$

PARAMETERS OF NPP IN SCHEME WITH N-STAGED RHFW

- Coefficient of turbine power decreasing:

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

- Turbine power using values of y_j:

$$H_i^p = h_0 - h_k - \sum_{j=1}^{n} \alpha_j \left(h_j - h_k \right) = H_i \left(1 - \sum_{j=1}^{n} \alpha_j y_j \right)$$

EFFICIENCY OF NPP IN SCHEME WITH N-STAGED RHFW

- Efficiency of theoretical NPP with RHFW:

$$\eta_t^p = \frac{H_0^p}{q_1^p} = \frac{H_0^p}{h_0 - h_{fw}} = \frac{\alpha_k \left(h_0 - h_{kt}\right) + \sum_{j=1}^{n} \alpha_j \left(h_0 - h_{jt}\right)}{h_0 - h_{fw}}$$

- Efficiency of real NPP with RHFW :

$$\eta_t^p = \frac{H_i^p}{q_1^p} = \frac{H_i^p}{h_0 - h_{fw}} = \frac{\alpha_k \left(h_0 - h_k\right) + \sum_{j=1}^{n} \alpha_j \left(h_0 - h_j\right)}{h_0 - h_{fw}}$$

EFFECT OF RHFW ON NPP EFFICIENCY

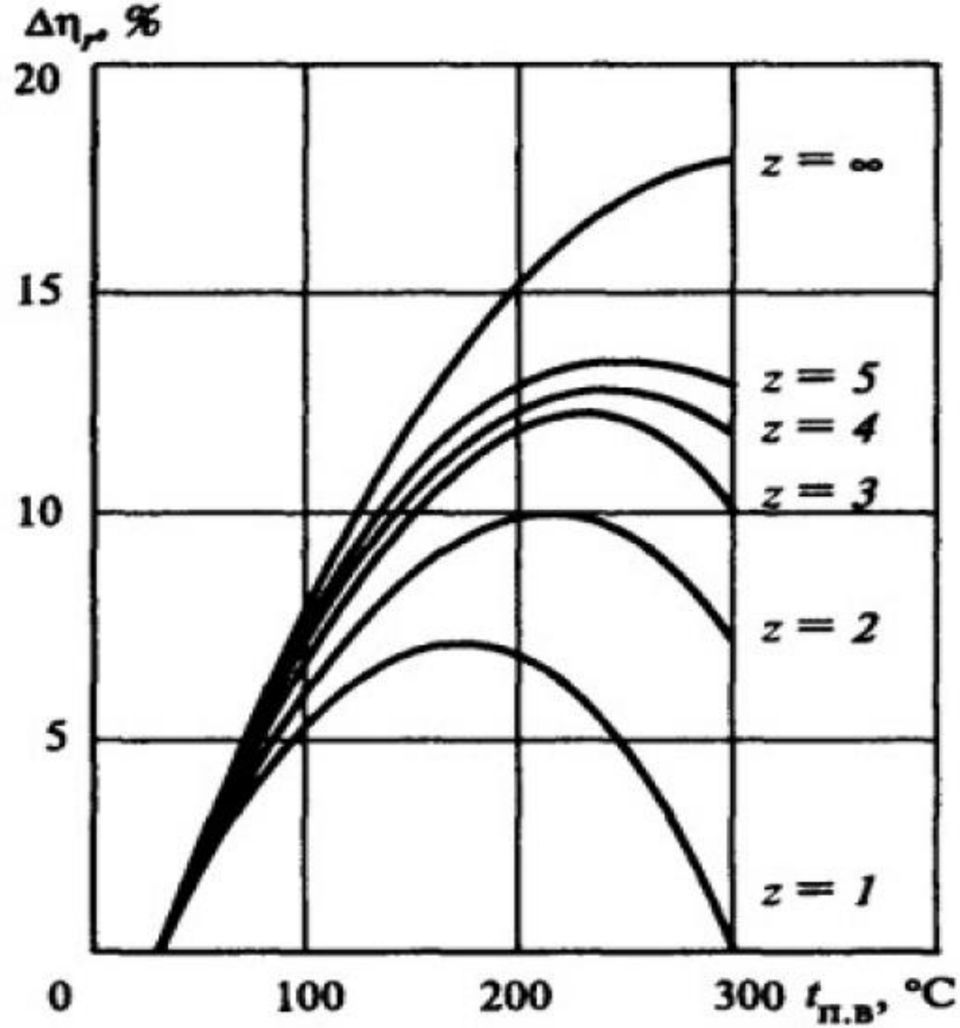
- Energy coefficient with regeneration:

$$A^p = \frac{\sum_{j=1}^{n} \alpha_j \left(h_0 - h_j\right)}{\alpha_k \left(h_0 - h_k\right)}$$

- Efficiency of theoretical NPP with RHFW:

$$\eta_i^{reg} = \eta_i^p \frac{1 + A^p}{1 + A^p \cdot \eta_i^p}$$

EFFECT OF NUMBER OF RHFW STAGES ON NPP EFFICIENCY



- Increasing z results into increasing efficiency.
- Maximal efficiency is obtained at optimal temperature of feed water.
- Optimal temperature of feed water increases with z.
- With increasing z the thermal efficiency decreases.

On practice the 7-8 stages of RHFW is applied. I allows to increase efficiency by 15-17 %.

EFFECT OF NUMBER OF RHFW STAGES ON NPP EFFICIENCY

- Power of turbine of NPP with RHFW:

$$N_i = G \cdot H_i^p = G \cdot H_i \cdot \left(1 - \sum_{j=1}^{n} \alpha_j \cdot y_j\right)$$

- Steam flow rate on turbine with RHFW:

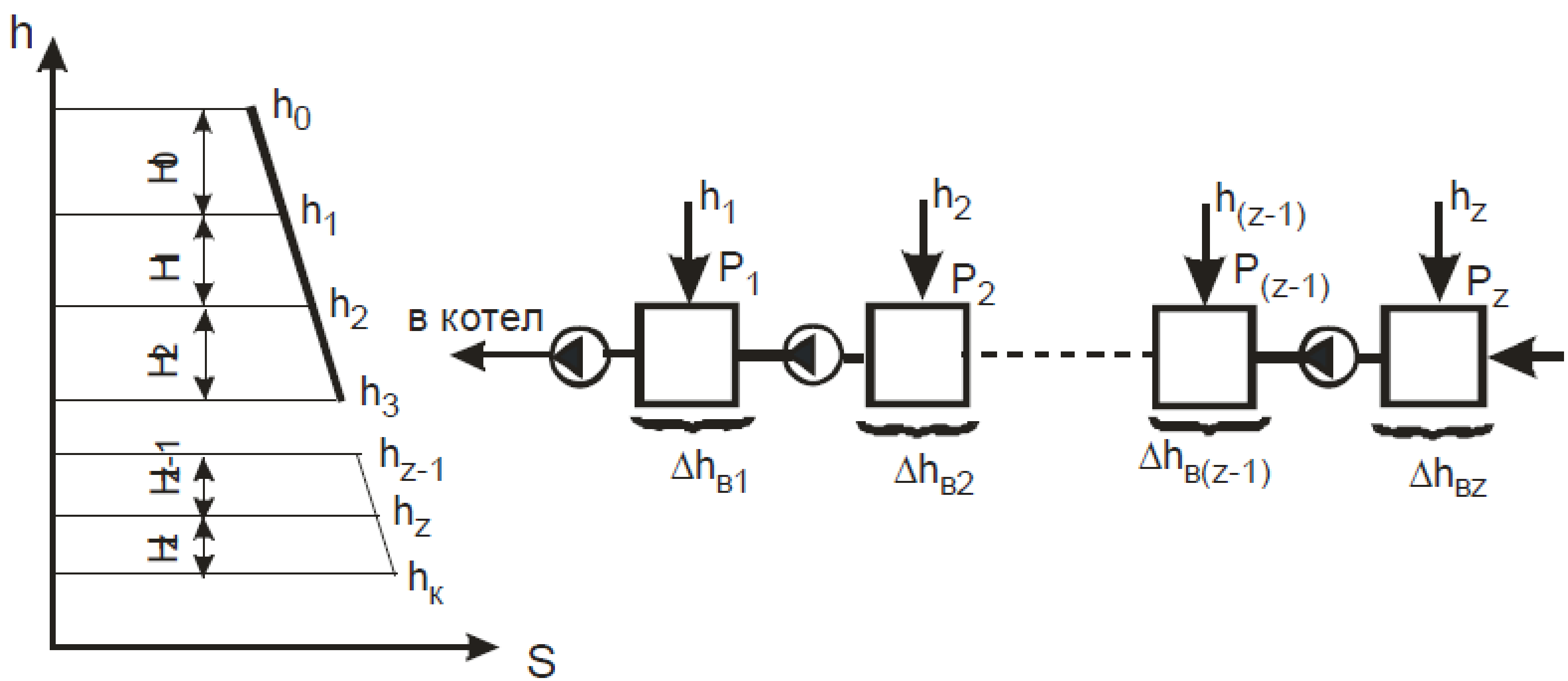
$$G = \frac{N_i}{H_i \cdot \left(1 - \sum_{j=1}^{n} \alpha_j \cdot y_j\right)}$$

<u>Note.</u> Steam flow rate in NPP with RHFW is larger in comparison with NPP without regeneration.

$$k_p = \frac{1}{1 - \sum_{j=1}^{n} \alpha_j \cdot y_j} > 1$$

CHOICE OF NUMBER OF BLEEDS AND PRESSURE

- To reach maximal thermal efficiency of NPP the different methods could be applied.



$$\Delta h_{B1} = H_0; \quad \Delta h_{B2} = H_1; \; \ldots \; \Delta h_{Bz} = H_{z-1}$$

EVEN DISTRIBUTION OF HEATING

- Assuming the heat taken from 1 kg of steam from one heater to another to be constant the maximal efficiency could be obtained at even distribution of enthalpy increasing.

$$\frac{\Delta h_{\text{B}1}}{\Delta h_{\text{B}2}} = \dots\dots\dots\dots = \frac{\Delta h_{\text{B}(z-1)}}{\Delta h_{\text{B}z}} = m$$

$$\Delta h_{\text{B}n} = \frac{(h_0^{'} - h_{\text{K}}^{'})}{z+1}$$

$$m = \sqrt[z]{\frac{\Delta h_{\Pi 1}}{\Delta h_{\Pi\text{K}}}}$$

EVEN DISTRIBUTION OF FEED WATER ENTROPY

$$\Delta s = \frac{(s_0^{'} - s_{\text{к}}^{'})}{z+1}$$

$$\Delta s = \frac{(s_{\text{пв}}^{'} - s_{к}^{'})}{z}$$

EVEN TEMPERATURE RELATION

$$\frac{T_1}{T_2} = \frac{T_2}{T_3} = \ldots\ldots\ldots = \frac{T_{z-1}}{T_z} = \frac{T_z}{T_к}$$

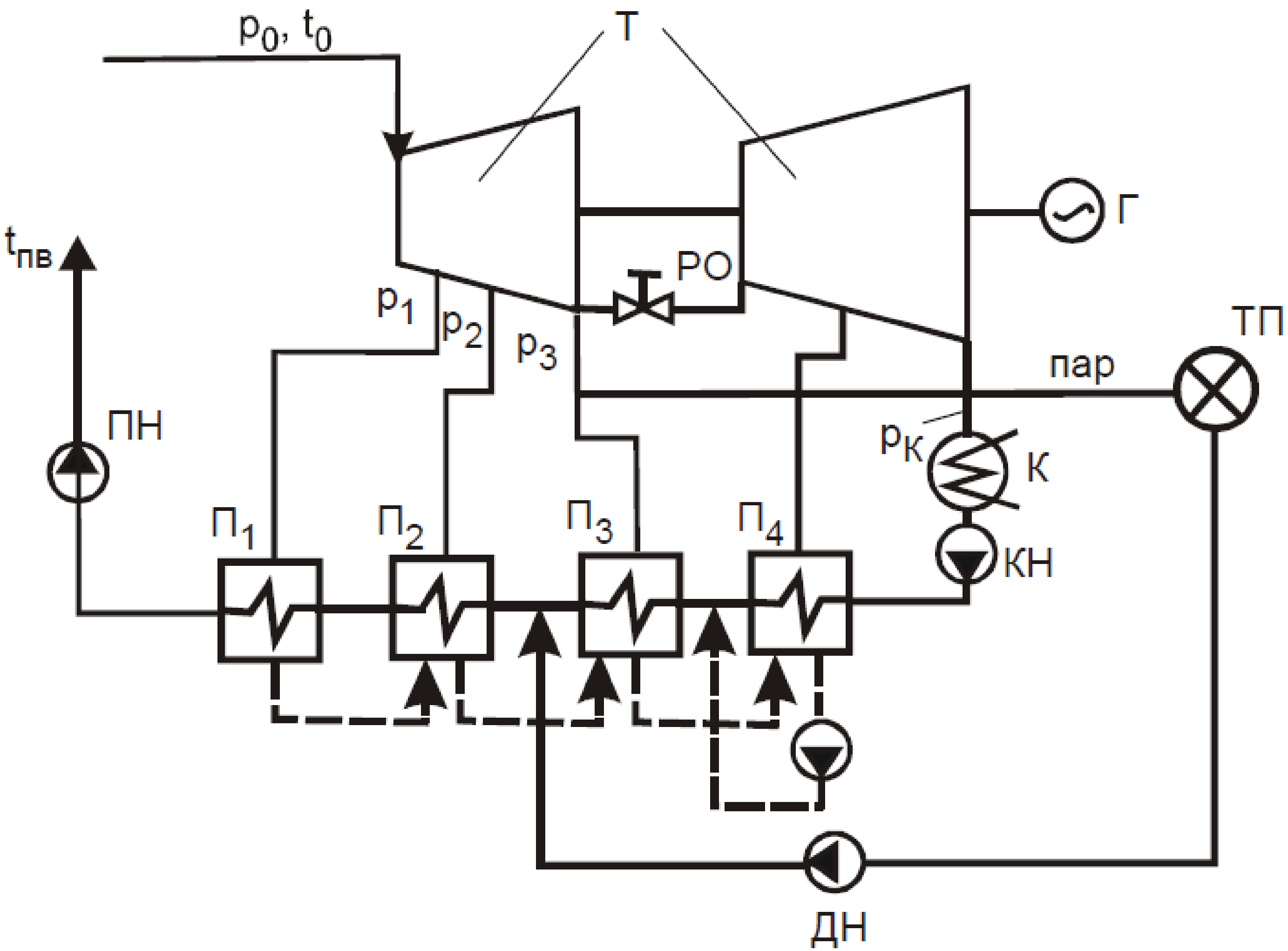
INDIFFERENT POINT

$$\frac{\Delta h_{\text{в}1}}{\Delta h_{\text{в}2} + \Delta h_{\text{пп}}} = \frac{\Delta h_{\text{в}2}}{\Delta h_{\text{в}3}} = m$$

$$\Delta h_{\text{пп}} = (h_{\text{пп}2} - h_{\text{пп}1}) \frac{h_0 - h_{\text{пп}1}}{h_0 - h'_1}$$

$$\Delta h_{\text{в}1} = 1{,}7 \cdot \Delta h_{\text{m}}$$

REGENERATION IN NPP WITH HEAT SUPPLY



CHOICE OF OPTIMAL TEMPERATURE OF FEED WATER

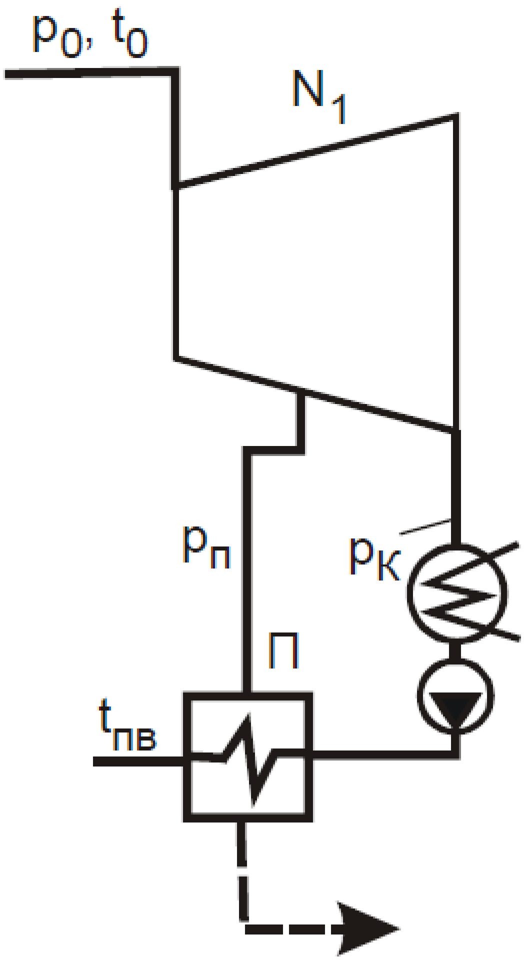
Choice of optimal feed water temperature is complex technic-economic task.

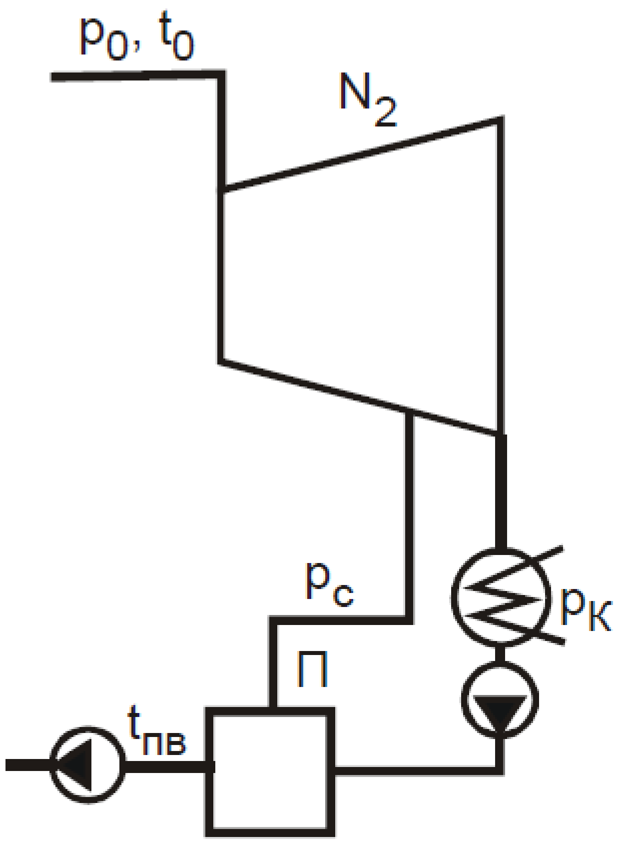
Factors affecting regeneration parameters:

- Specific power of equipment;
- Initial parameters of steam;
- Cost of materials and fuel.

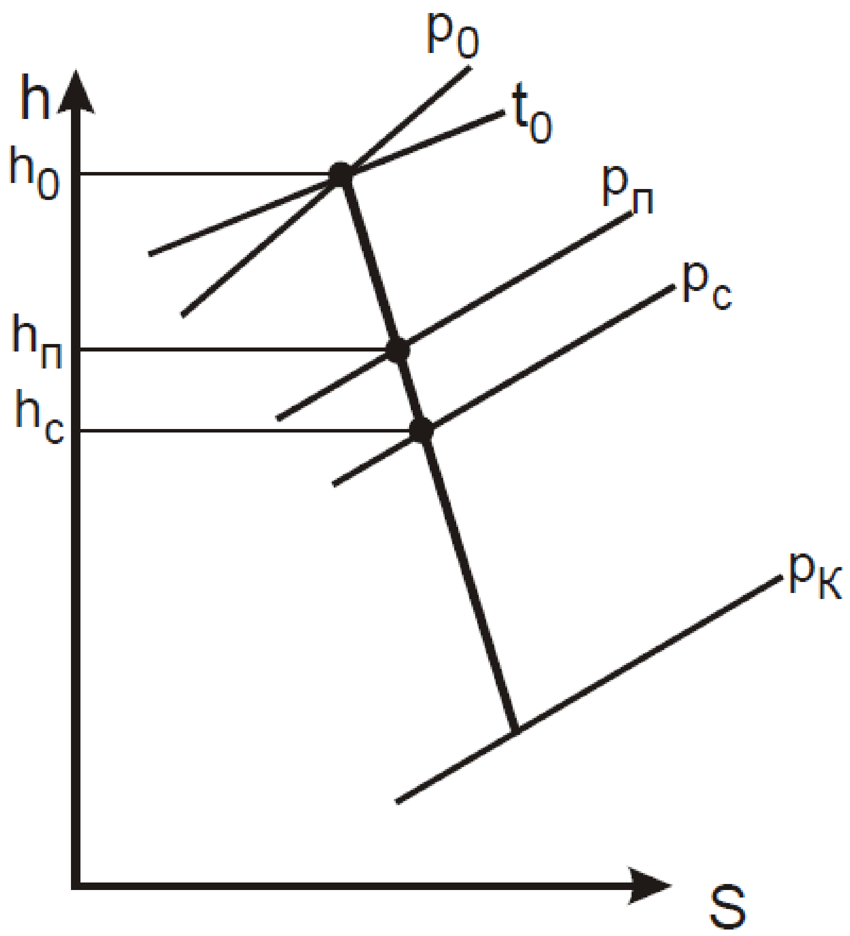
- Taking into account economic factors the amount of regenerative heaters is chosen to be 7-9 in Russia and up to 11 abroad. The technic-economic optimal temperature of feed water is lower than thermodynamic optimal.

COMPARISON OF SURFACE-TYPE AND MIXING HEATERS





COMPARISON OF SURFACE-TYPE AND MIXING HEATERS



MIXING HEATERS

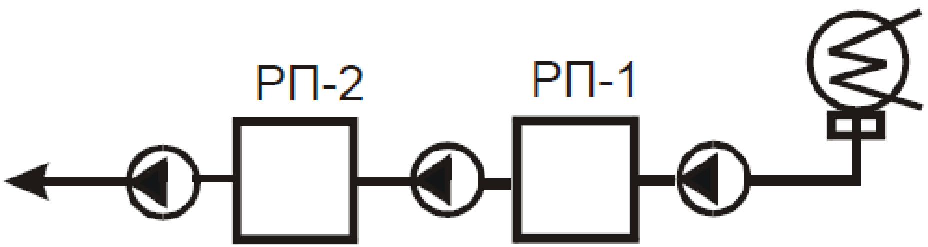
Advantages:

- Simplicity;
- Lower cost;
- Higher reliability;
- Simplicity of exploitation and repairs;
- Lesser concentration of metals and oxides.
- **NO UNDERHEATING.**

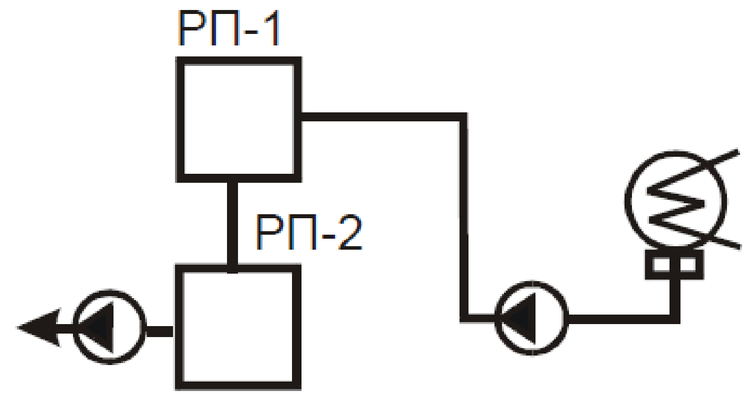
Disadvantages:

- Need for additional pumps;
- Need for additional protection from droplets entering turbine (hard to realize at high pressures).

SCHEMES OF MIXING HEATERS



а



б

The heaters of mixing type is applied for the first two steps of regenerative heating.

SURFACE HEATERS

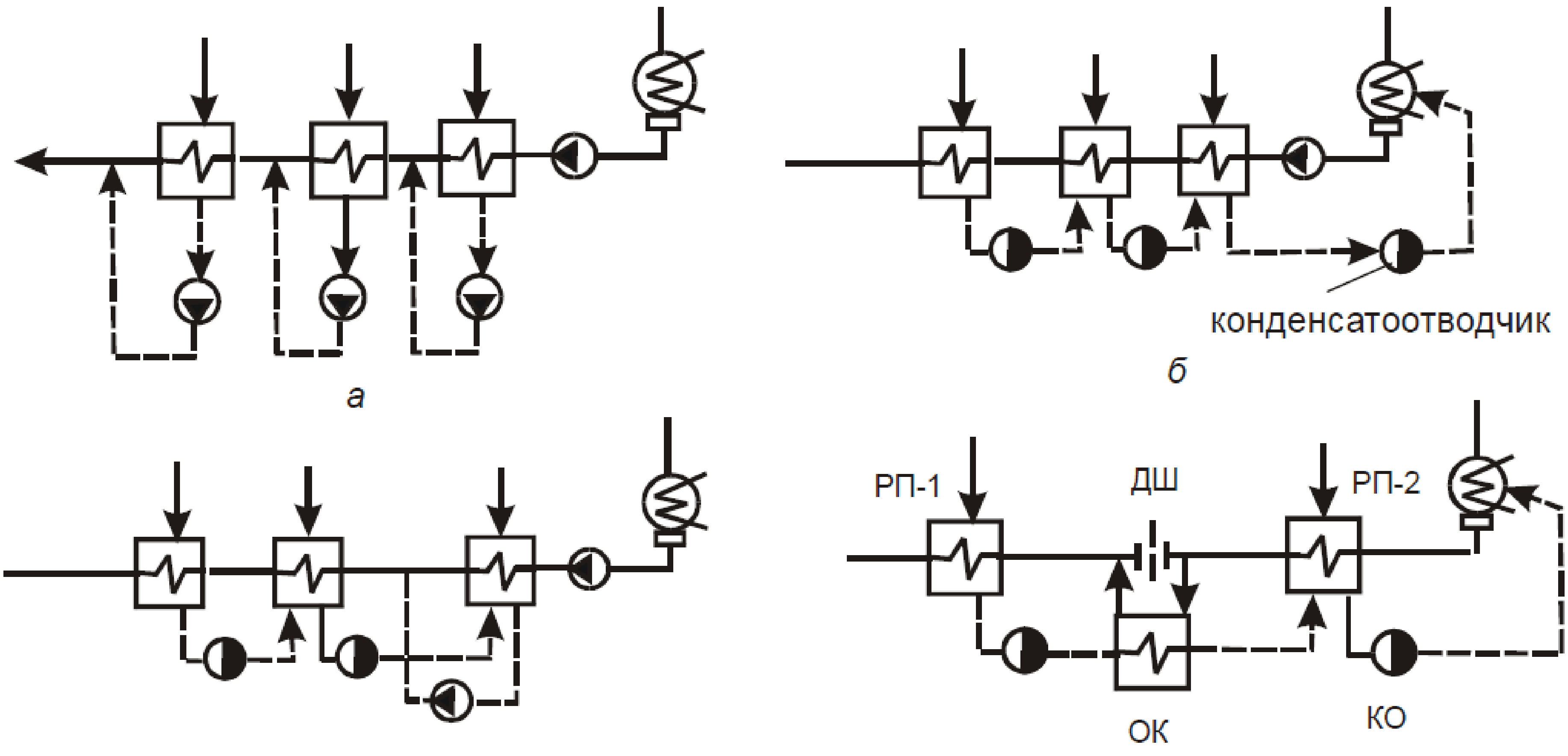
Advantages:

- Independence of steam and water pressures;
- Possibility to apply one pump.

Disadvantages:

- Complexity;
- Lesser reliability;
- Higher costs;
- **UNDERHEATING.**

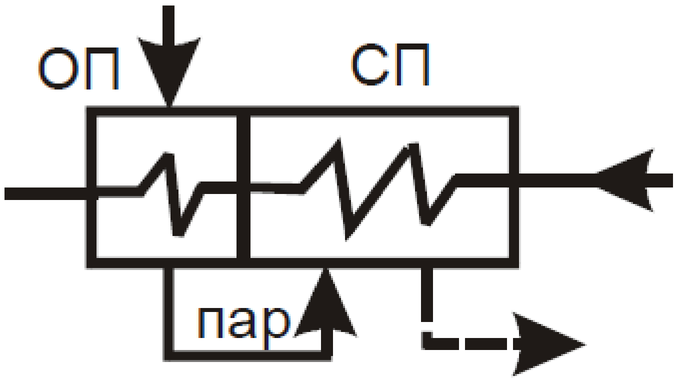
SCHEMES OF SURFACE HEATERS



COMPARISON OF SCHEMES

<table>
<tr><th>Scheme</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>A</td><td>Maximal efficiency</td><td>Many pumps pumping water with high temperature</td></tr>
<tr><td>B</td><td>Simplicity
No pumps needed</td><td>Steam condensate push out steam from next heaters
Additional losses into condenser</td></tr>
<tr><td>C</td><td colspan="2" rowspan="2">Intermediate solution between schemes A and B
Aim: decrease “pushing out”
Main feature: temperature of condensate in drainage cooler is higher by 10-15 °C in comparison with feed water temperature.</td></tr>
<tr><td>D</td></tr>
</table>

STEAM COOLER

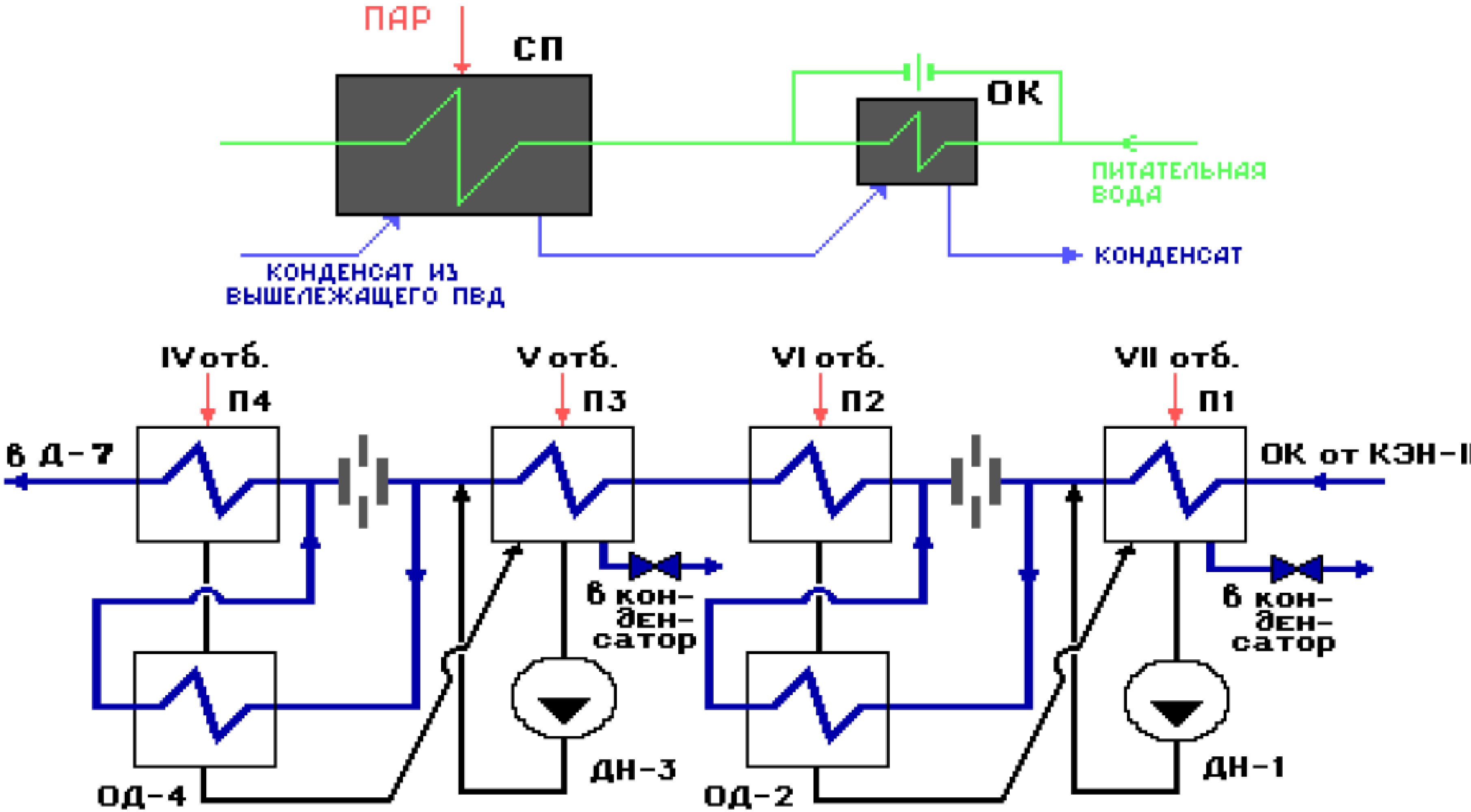


Temperature of steam after steam cooler is higher by 10-15 °C than saturation temperature.

Application of steam cooler gives:

- *higher feed water temperatures on the outlet;*
- *increased efficiency of regeneration;*
- *increased bleed steam consumption.*

DRAINAGE/CONDENSATE COOLER



THANK YOU FOR YOUR ATTENTION