ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

NPP STEAM GENERATORS

Thermal technological schemes of NPP SGs

Lecture plan

1. Thermal technological schemes s of steam generators with water coolant.
2. Thermal technological schemes of steam generators with liquid metal coolant.
3. tQ – diagrams

Steam generator definition

NPP Steam Generator is a heat exchange device that generates nonradioactive steam in the second (third) loop using the heat of the source coolant.

Question. Where is the error here?

Coolant is a medium (agent) that passes through the reactor core and draws off heat from the fuel elements (a medium transferring heat to a SG).

Working fluid is a medium that converts heat (thermal energy) into mechanical energy (a medium that receives heat in a SG and does not change its aggregate state).

Coolant and working fluid definitions

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Working fluid is a medium that converts heat (thermal energy) into mechanical energy (a medium that receives heat in a SG and change its aggregate state).

Notion of thermal technological schemes of SG

Thermal technological scheme of a SG is a scheme that illustrates graphically the heat transfer process from the coolant to the working fluid.

The heat transfer surface of a SG is commonly divided into 3 zones (elements) that perform their specific functions:

- economizer (E),
- evaporator (Ev),
- primary superheater (PS or PSH)
- secondary (intermediate) superheater (reheater) (SS or SSH)

Question. Which zone (heating surface element) is there always in the steam generator?

- economizer (E),
- evaporator (Ev),
- primary superheater (PS or PSH)
- secondary (intermediate) superheater (reheater) (SS or SSH)

tQ-diagram of SG

tQ-diagram is a diagram that illustrates graphically how the coolant’s and working fluid’s temperatures are distributed over the SG ‘s characteristic zones.

tQ-diagram is plotted in accordance with the chosen thermal technological scheme of a steam generator and on the basis of the results of heat balance equations.

Heat and material balances

Heat and material balance equations are used to determine the heat content which is transferred both in a steam generator as a whole and in its separate zones: economizer, evaporator, superheater, and reheater (intermediate superheater).

The structure of the heat and material balance equation system of a SG is dependent on its thermal technological scheme.

Thermal technological scheme of water-heated SGs

- Superheated steam generator with natural circulation.
- Once-through superheated steam generator.

Structure and parameters of SG’s thermal technological scheme with water coolant

Water – low-temperature coolant → Saturated or slightly superheated steam; no secondary superheating

Low water saturation temperature → Low steam pressure

Superheated steam generator with natural circulation (with combined E+Ev)

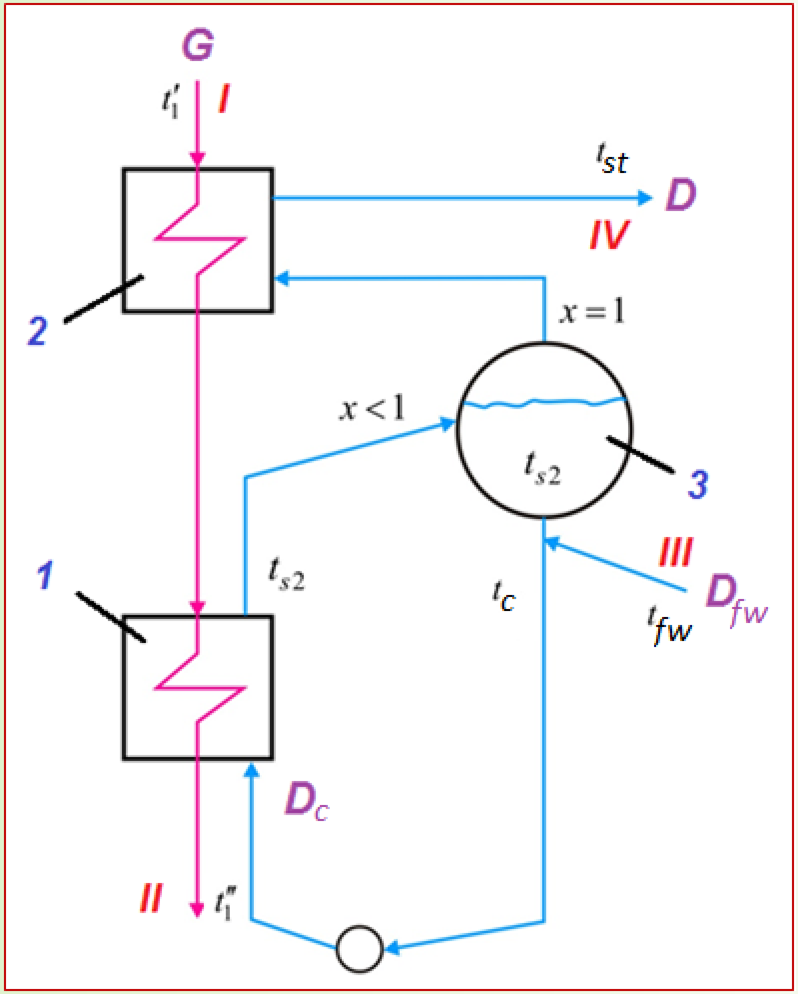


Fig. Cycle arrangement scheme for superheated steam generator with NC in evaporator

1 – economizer + evaporator;
2 – superheater;
3 – separation volume;
I, II – coolant inlet and outlet;
III – feedwater inlet from the turbine;
IV – steam outlet;
G – coolant flow rate, kg/s;
D – steam flow rate, kg/s;
D_{fw} – feedwater flow rate, kg/s;
D_c – circulation water flow rate, kg/s;

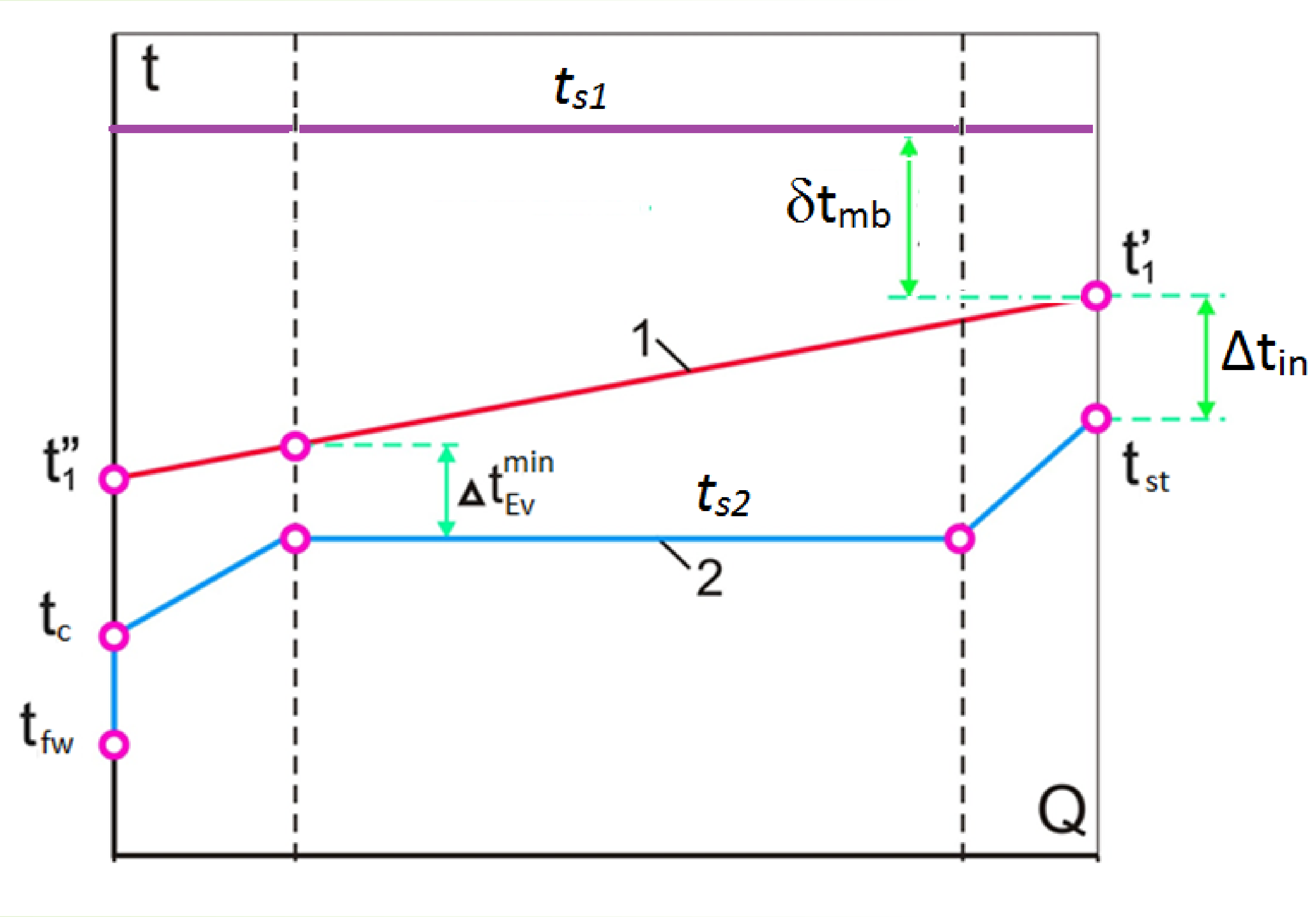
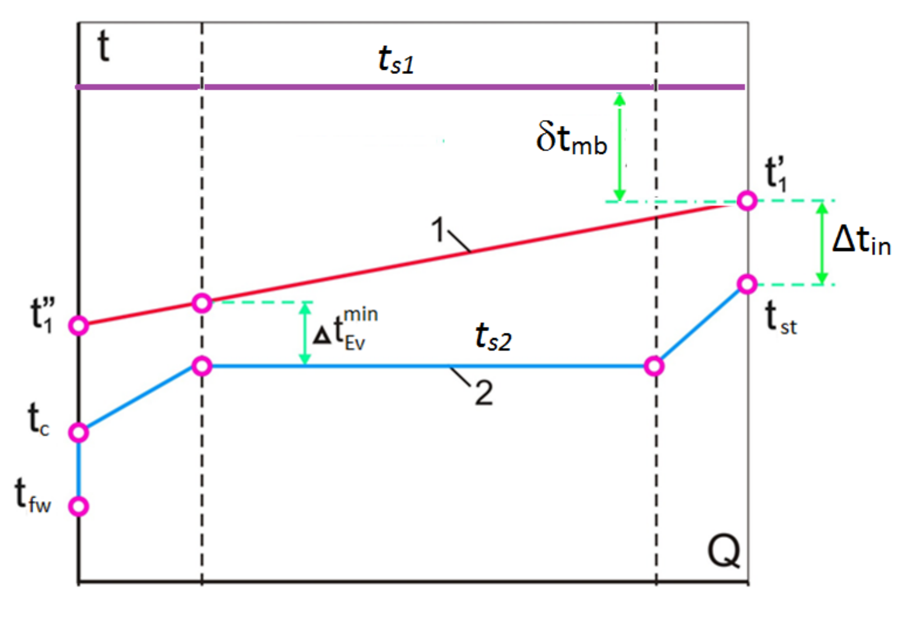


Fig. tQ- diagram for superheated steam generator with natural circulation in evaporator

Characteristic temperatures on tQ-diagram

- t'_1 is coolant temperature at the SG inlet;
- t''_1 is coolant temperature at the SG outlet;
- t_{st} is temperature of generated steam in SG;
- t_{s1} is saturation temperature at pressure p_1;
- t_{s2} is saturation temperature at pressure p_2;
- t_{fw} is feedwater temperature;
- t_c is circulation temperature;
- Δt_{Ev}^{min} is min temperature difference in evaporator;
- δt_{mb} is margin to boiling in reactor;
- $\Delta t_r = (t'_1 - t''_1)$ is coolant heating in reactor (cooling of the coolant in the steam generator);
- Δt_{in} is temperature difference at the inlet of the coolant to the SG



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Let's consider the most important parameters

- t'_1 – coolant temperature at the SG inlet;

Coolant temperature t'_1 at SG inlet

Coolant temperature t'_1 is restricted by two conditions:

- coolant must not boil at the reactor outlet;
- the maximum operating temperature of the fuel element cladding (Zr + 1% Nb) should not exceed 360 ° C.

$$\left(t'_1\right)_{\max} \le t_{s1} - \delta t_{mb}$$

$$\left(t'_1\right)_{\max} \le 360\ ^{\circ}C$$

Note: $\delta t_{mb} = 15 \ldots 25\ ^{\circ}C$ is margin to boiling in reactor;

Coolant temperature t'_1 at SG inlet

Coolant pressure in the reactor is taken as the max possible depending on its vessel's manufacturing conditions.

Considering the contemporary Russian and world reactor construction practice this pressure is equal to 16..17 MPa.

We can calculate the maximum temperature of the coolant at the reactor outlet for a pressure of 16 and 17 MPa

$$\left(t_1'\right)_{\max} \le t_{s1} - \delta t_{mb} = (352,3...347,4) - (25...15) \approx 337...322\ ^{\circ}C$$

Effect of coolant pressure on coolant inlet temperature t_1'

Calculation of temperature t_1''

$$t_1' = t_{s1} - \delta t_{mb}$$

p_1=16 MPa; t_{s1}=347.4 °C ; t_1'= t_{s1}- δt_{mb} =347.4-20 ≈ 327 °C**;**

p_1=17 MPa; t_{s1} =352.3 °C ; t_1'= t_{s1}- δt_{mb} **=** 352.3-20 ≈ 332 °C.

Type of reactor	$(p_1)_{out}$, MPa	t_s, °C	t'_1, °C	t''_1, °C	δt_{rs} , °C	Δt_r , °C
VVER-1000	15,7	345,8	290	320	25,8	40
VVER-1200	16,2	348,4	298,6	329,7	18,7	31,1
EPR-1500	15,2	344,8	295,3	329,9	14,9	34,6

Coolant temperature t''_1 at the SG outlet

Let's consider two cases:

1 Minimum temperature difference in evaporator is constant value

$$\Delta t_{Ev}^{min} = \text{const}$$

2 The saturation temperature in SG t_{s2} is constant value

$$t_{s2} = \text{const}$$

1 Minimum temperature difference in evaporator is constant value

$$\Delta t_{Ev}^{\min} = \text{const}$$

$\Delta t_r \Uparrow$

Decrease in flow rate G and energy consumption needed for circulation, reduction in the size of the 1st-circuit pipelines

Decreasing t_{s2} in SG, hence, decreasing p_2

$$\Downarrow t_{s2} \approx t_1' - \Uparrow \Delta t_r - \Delta t_{Ev}^{\min}$$

$$\Downarrow G = Q \big/ \left(c_p \cdot \Uparrow \Delta t_p \right)$$

2 The saturation temperature in SG t_{s2} is constant value

$$t_{s2}=\text{const}$$

$\Delta t_r \Uparrow$

Decreasing in flow rate G and energy consumption needed for circulation, reduction in the size of the 1st-circuit pipelines

Decreasing Δt^{min}_{Ev} in SG, hence, increase in heating surface and steam generator cost

$$t_{s2} \approx t_1' - \Uparrow \Delta t_r - \Downarrow \Delta t_{Ev}^{\min}$$

$$\Downarrow G = Q \big/ \left(c_p \cdot \Uparrow \Delta t_p \right)$$

$$\Uparrow F = Q \big/ \left(k \cdot \Downarrow \Delta t_{pavr} \right), \quad \Delta t_{pavr} = f\left(\Delta t_{Ev}^{\min} \right)$$

Conclusions regarding temperature t''_1 at the SG outlet

At the specified inlet temperature the outlet temperature, t''_1 is determined by the coolant heating in the reactor

$$t_1'' = t_1' - \Delta t_r$$

The coolant heating Δt_r in the reactor affects:

- coolant's flow rate G ;
- generated steam pressure p_2 (the saturation temperature in SG t_{s2});
- area of the heating surface F.

Note: <u>optimum value</u> $\Delta t_r \approx 30\ ^\circ C$

$$\Delta t_{Ev}^{\min} = 10 \ldots 20\ ^\circ C$$

Saturation temperature t_{s2} of working fluid in SG

$$t_{s2} \approx t_1' - \Delta t_r - \Delta t_{Ev}^{\min} = 322 - 30 - (10\ldots20) = 282\ldots272\ ^\circ C$$

These saturation temperature values correlate with the values of generated steam pressure

$$p_2 \approx 5,67\ldots6,6\ MPa$$

Steam temperature at SG outlet

At specified coolant temperature t'_1 the generated steam temperature t_{st} is determined by the temperature difference in the inlet section of SG

$$t_{st} = t'_1 - \Delta t_{in}$$

Note: <u>optimum</u> value $\Delta t_{in} = 10 \ldots 15\ ^{\circ}C$

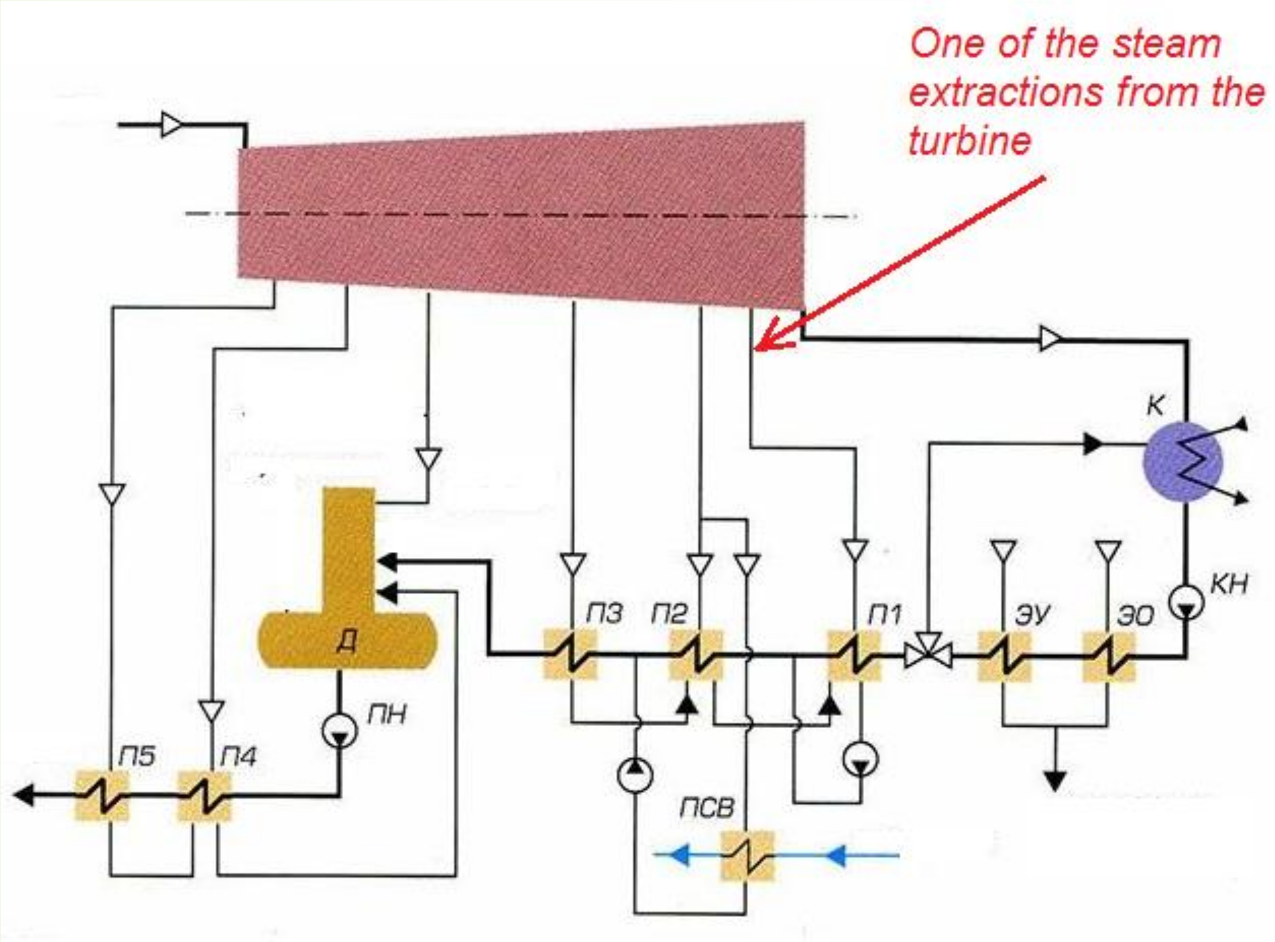
Feedwater temperature

is determined by the variational optimization results for steam-turbine and steam-generating units

$$t_{fw}^{optim} = t_c' + \left(0{,}8 \ldots 0{,}9\right) \cdot \frac{t_0 - t_c'}{z - 1} \cdot z$$

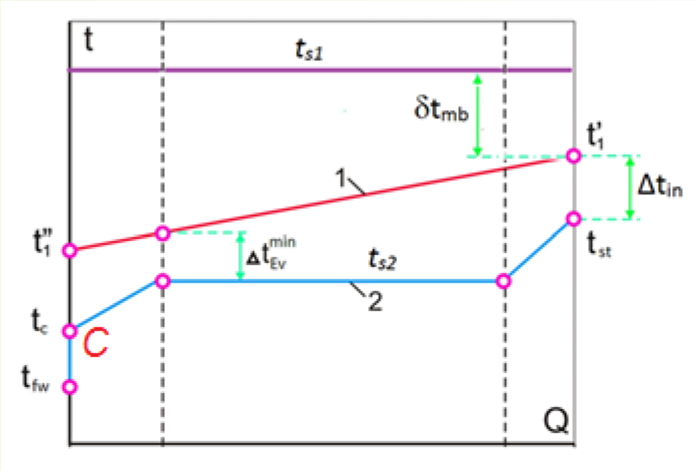
here z is the number of regenerative heating steps of feedwater

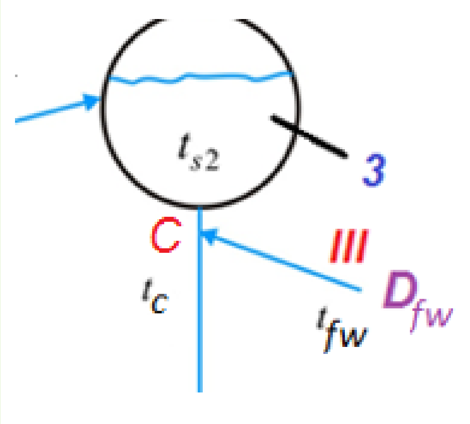
Question. How many stages of regenerative heating does this steam turbine plant have? z=…



Circulation temperature

is determined from the heat balance for mixing point *C*



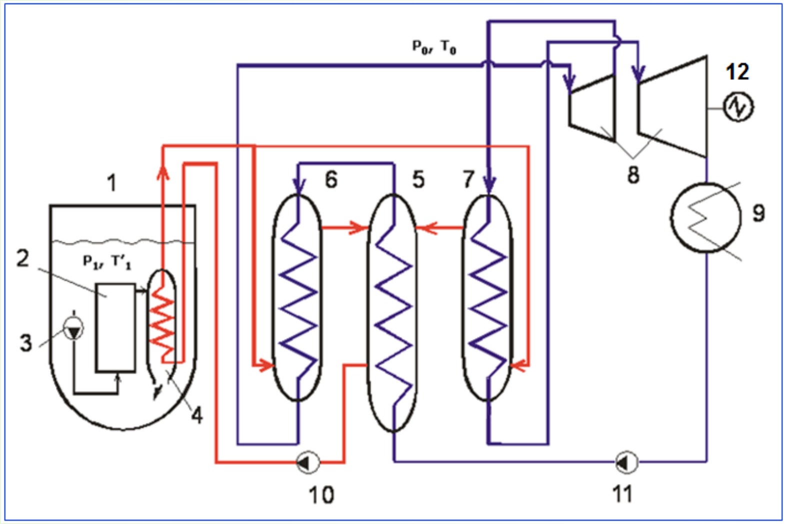


$$D_c \cdot h_c = D \cdot h_{fw} + (D_c - D) \cdot h_2'$$

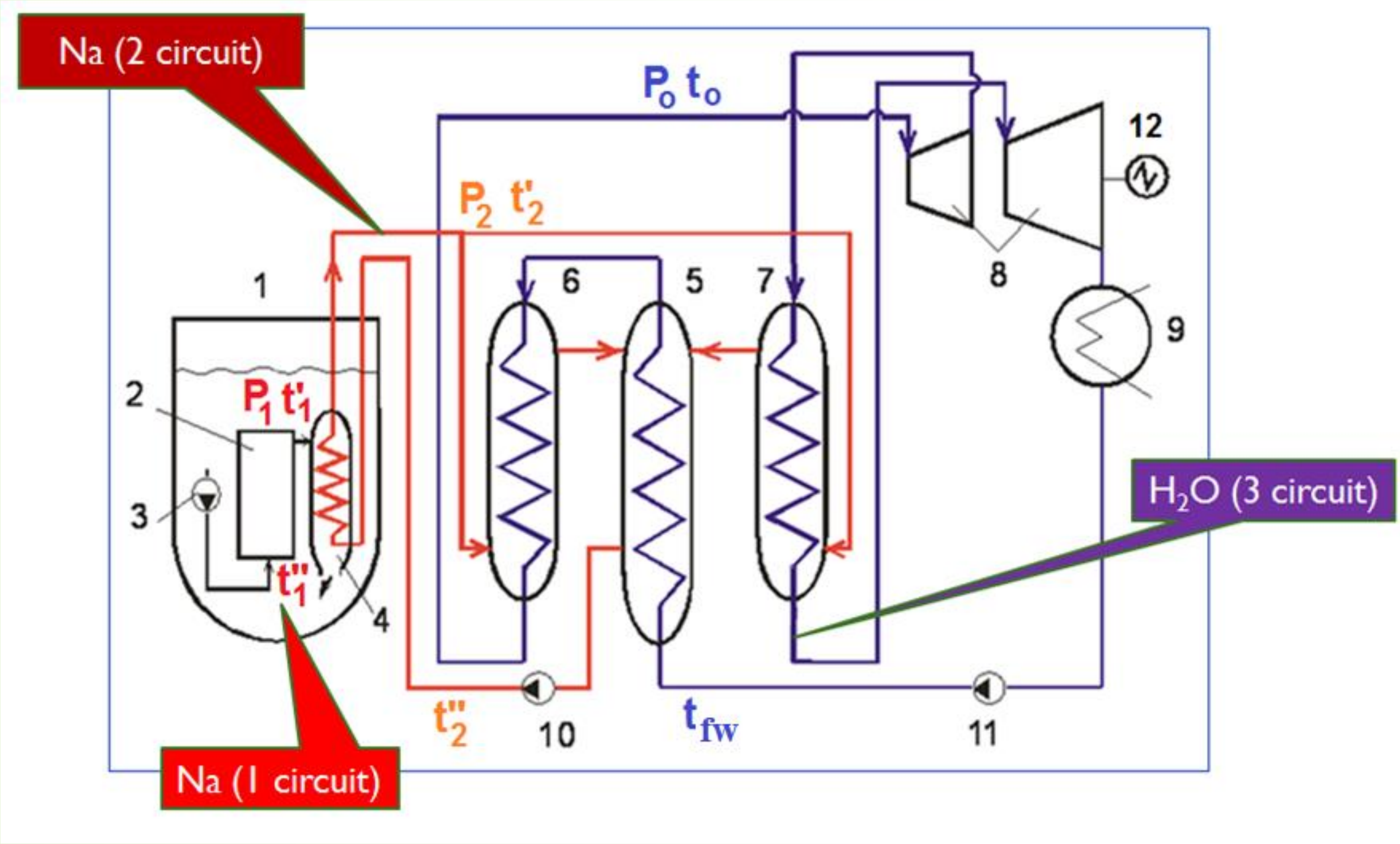
$$h_c = \frac{h_{fw} + (k_c - 1) \cdot h_2'}{k_c}$$

$$t_c = f(h_c, p_2)$$

Cycle arrangements of SGs with liquid metal coolants



Cycle arrangement scheme of SG with BN-600



Legend to the scheme of power unit with BN-600 reactor

1 – reactor;

2 – core;

3 – reactor coolant pump;

4 – heat exchanger Na-Na;

5, 6, 7 – section of the steam generator;

5 – evaporator module (E+Ev);

6 – primary superheater module (SH or PSH);

7 - secondary superheater (reheater) module (SSH);

8 – turbine;

9 – condenser;

10 - circulation pump of the 2nd circuit;

11 – feed pump;

12 – electric generator.

Main technical parameters of SG with BN-600

Parameters	SG surfaces		
	Evaporator	Superheater (SH)	intermediate superheater (SSH)
Thermal power, MW	312	99	70
Coolant flow rate, t/h	6800	4050	2750
Working fluid flow rate, t/h			
Temperature:			
- coolant inlet/outlet, $^{o}C/^{o}C$	450/320	520/450	520/450
- working fluid inlet/outlet, $^{o}C/^{o}C$	241/360	360/505	360/505
Working fluid pressure, MPa	15	14	2,5
Tube number	333·8	241·8	235·8
Heat transfer coefficient, $W/(m^2 \cdot K)$	2410 4470 1720	1380	530

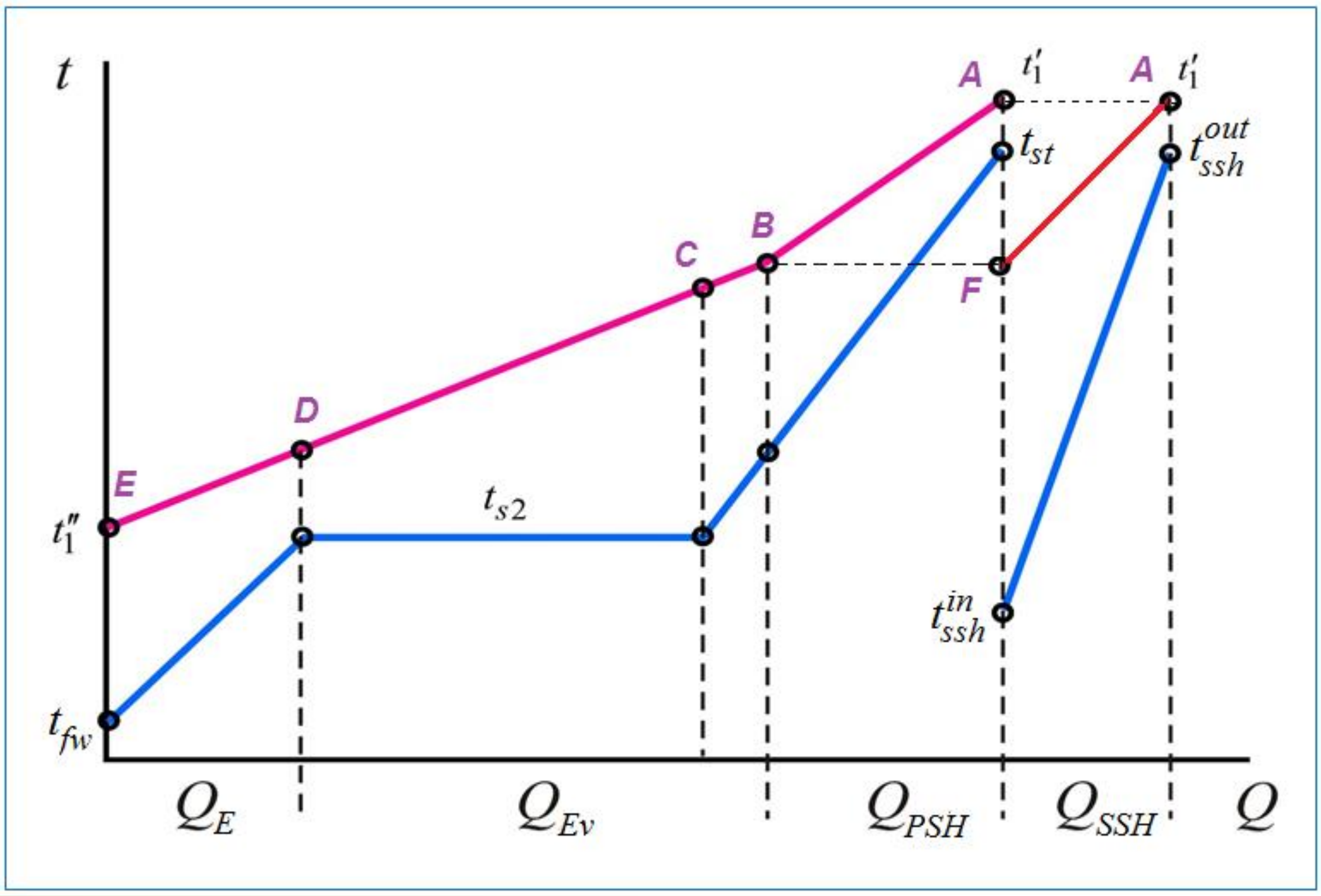


Fig. tQ- diagram of superheated steam generator with LMC (SG BN-600)

Characteristic temperatures on tQ - diagram

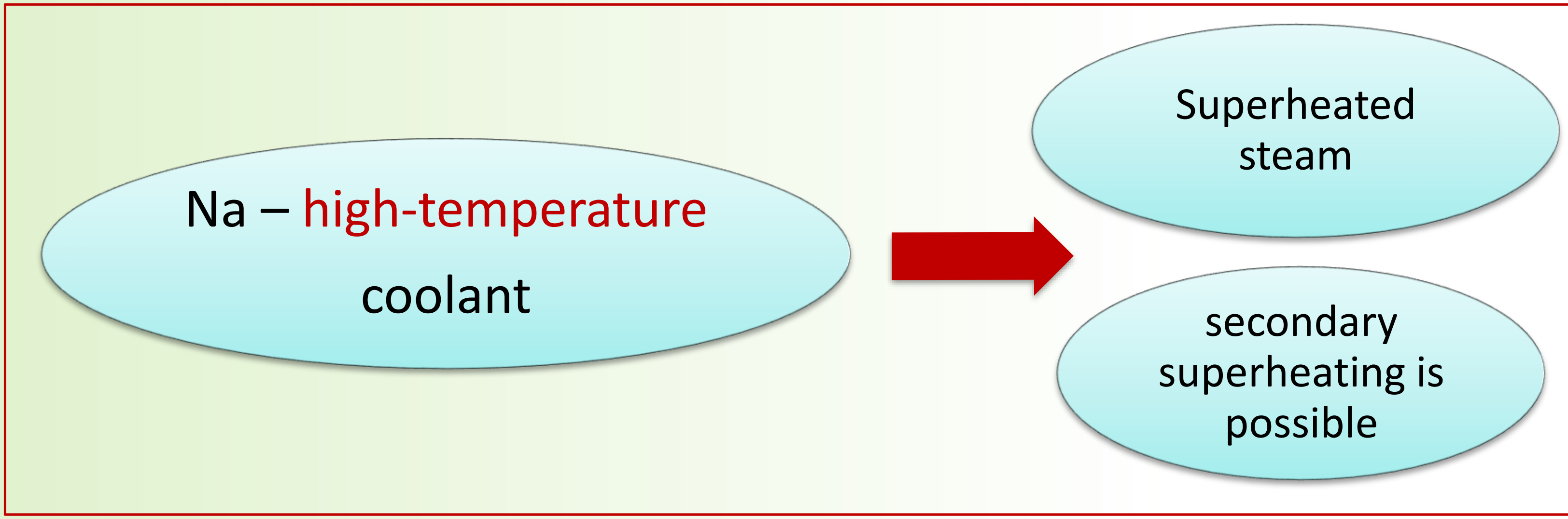
- t'_1 – coolant temperature at SG inlet;
- t''_1 - coolant temperature at SG outlet;
- t_{st} – temperature of generated steam in SG;
- t_{s2} – saturation temperature at pressure p_2;
- t_{fw} – feedwater temperature;
- Δt_r – water heating in reactor

Cycle arrangements of SGs heated by liquid metal coolants

Na – high-temperature coolant → Superheated steam; secondary superheating is possible

Low heat capacity of LMC → Significant changes in coolant temperature

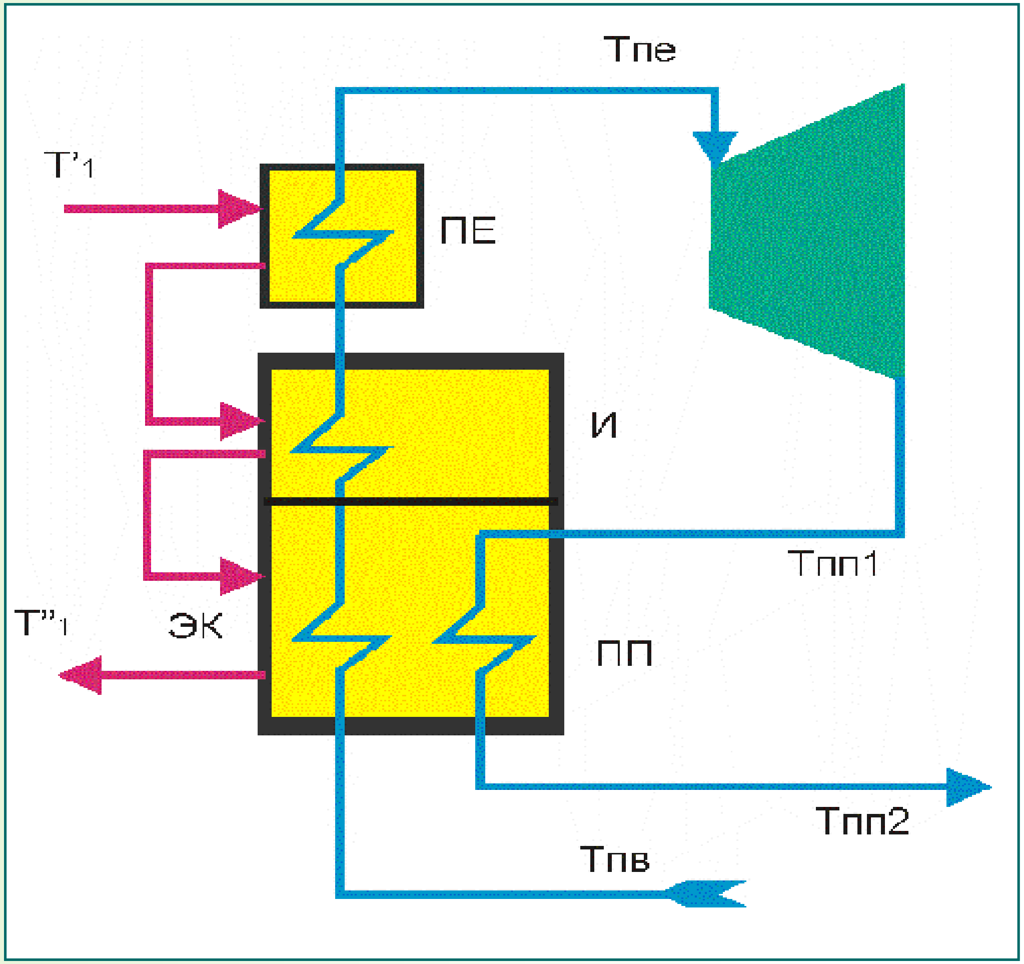
Cycle arrangements of SGs heated by liquid metal coolants



Max inlet temperature t'_1 is identified taking into account:

- necessity to obtain steam with high parameters (superheated steam cycle);
- possibility to ensure reliable temperature of the reactor (cladding temperature)

Low-temperature secondary superheating in SGs of NPP with liquid metal coolants



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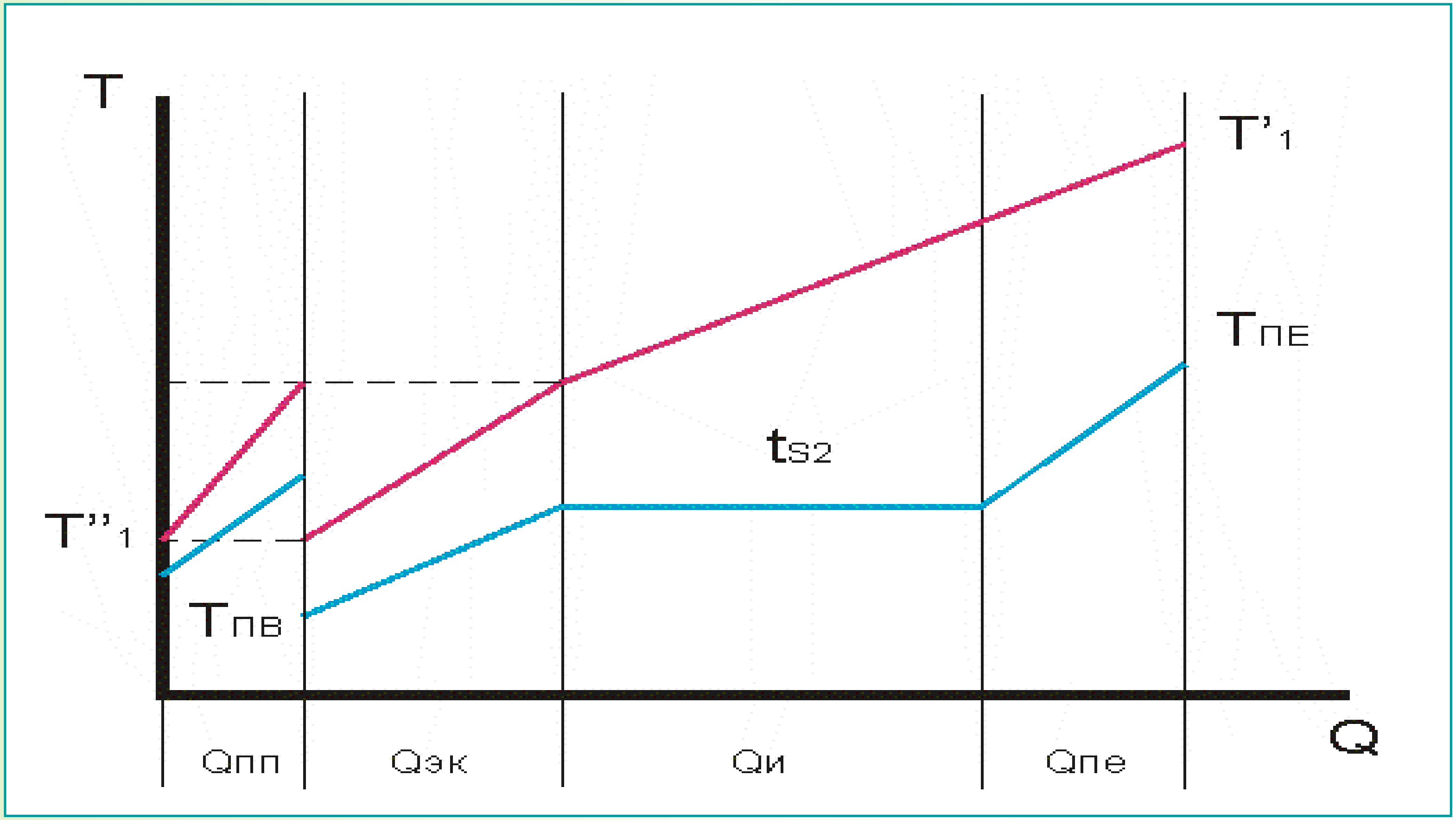

Fig. TQ-diagram for LMC SG with low-temperature secondary superheating

Thank you for attention