ТОМСКИЙ
ПОЛИТЕХНИЧЕСКИЙ
УНИВЕРСИТЕТ

NPP STEAM GENERATORS

Lecture 3. Cycle arrangement of NPP SGs

Lecture plan

1. Cycle arrangement of NPP steam generators with water coolant.
2. Cycle arrangement of NPP steam generators with liquid metal coolant.
3. tQ – diagrams

Notion of cycle arrangement of SG

Cycle arrangement 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)
- secondary (intermediate) superheater (reheater) (SS)

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 cycle arrangement 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 cycle arrangement scheme.

Cycle arrangement of water-heated SGs

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

Structure and parameters of SG's cycle arrangements with water coolant

Water – low-temperature coolant

→

Saturated or moderately superheated steam

no secondary superheating

Low water saturation temperature

→

Low steam pressure

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

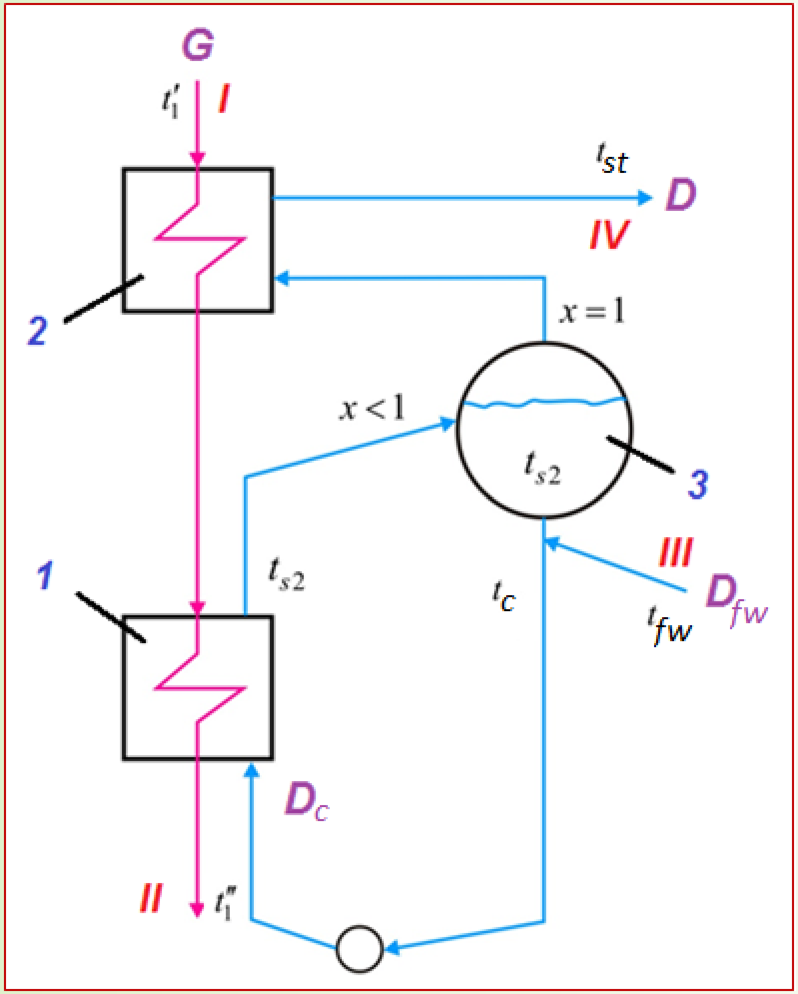


Fig. Cycle arrangement scheme for superheated steam generator with NC in evaporator

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;

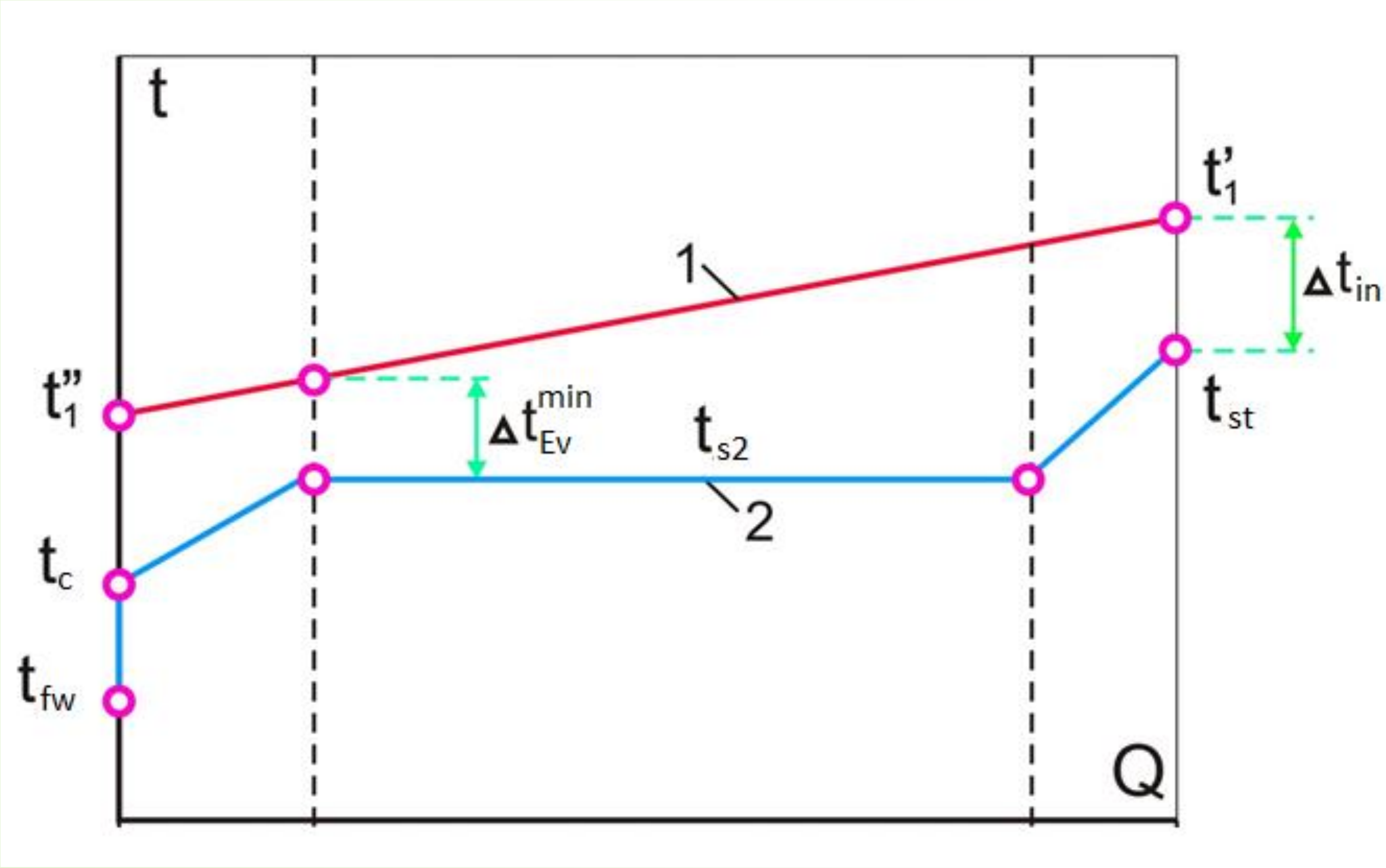


Fig. tQ- diagram for superheated steam generator with natural circulation in evaporator

Characteristic temperatures on tQ-diagram

- t'_1 – coolant temperature at the SG inlet;
- t''_1 - coolant temperature at the SG outlet;
- t_{st} – temperature of generated steam in SG;
- t_{s1} – saturation temperature at pressure p_1;
- t_{s2} – saturation temperature at pressure p_2;
- t_{fw} – feedwater temperature;
- t_c - circulation temperature;
- Δt_{Ev}^{min} - min temperature difference in evaporator;
- δt_{rs} – margin to boiling in reactor;
- Δt_r – coolant (water) heating in reactor;

Coolant temperature t'_1 at SG inlet

Coolant temperature t'_1 is restricted by two conditions:

- coolant must not boil at the reactor outlet;
- max operating temperature of the fuel elements' cladding (Zr+1%Nb) must not be exceeded (not more than 360 °C)

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

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

Note: $\delta t_{rs} = 15 \ldots 25\ ^\circ C$

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 MPa.

$$\left(t_1'\right)_{\max} \le t_{s1} - \delta t_{rs} = 347,4 - 25 \approx 322\ ^\circ C$$

Effect of coolant pressure on coolant inlet temperature t_1'

Calculation of temperature t_1''

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

p_1=16 MPa; t_{s1}=347.4 °C ; $t_1' = t_{s1} - \delta t_{rs}$ =347.4-25 ≈ 322 °C;

p_1=17 MPa; t_{s1} =352.3 °C ; $t_1' = t_{s1} - \delta t_{rs}$ = 352.3-25 ≈ 327 °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

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 the coolant's flow rate G and the generated steam pressure p_2 (the saturation temperature in SG t_{s2})

$$t_{s2} \approx t'_1 - \Delta t_r - \Delta t_{Ev}^{\min}$$

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

Note: <u>optimum value</u> $\Delta t_{Ev}^{мин} = 10...20\ ^{\circ}C$

Analysis of coolant heating effect

At specified and unchangeable min temperature difference in evaporator Δt_{Ev}^{min} = 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

Considering these factors

$$\Delta t_r^{optimal} \approx 30\,^{\circ}C \quad if \;\; t_1'' \approx 290\,^{\circ}C$$

Saturation temperature t_{s2} of working fluid in SG

$$t_{s2} \approx t_1' - \Delta t_r - \Delta t_{Ev}^{\min} = 322 - 30 - (10...20) = 282...272\ ^\circ C$$

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

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

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

$$t_{fw}^{optimal} = t_c' + (0,8...0,9) \cdot \frac{t_0 - t_c'}{z - 1} \cdot z$$

here z is the number of regenerative heating steps of feedwater

Circulation temperature

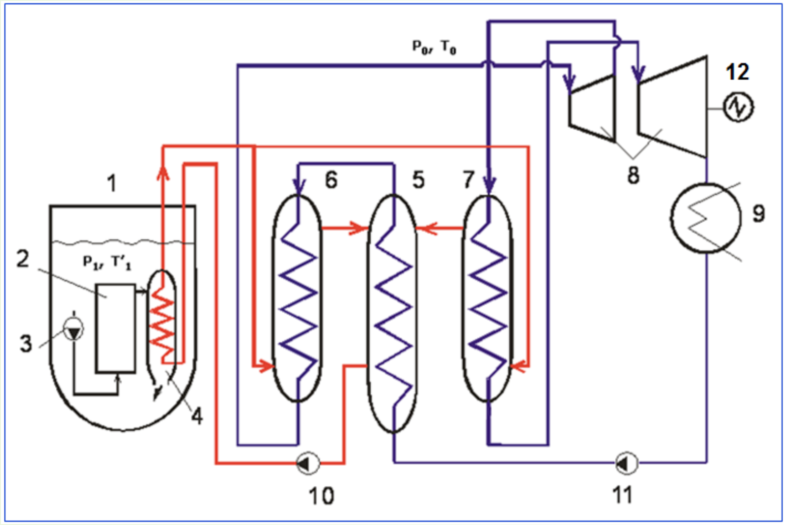
is determined from the heat balance for mixing point

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

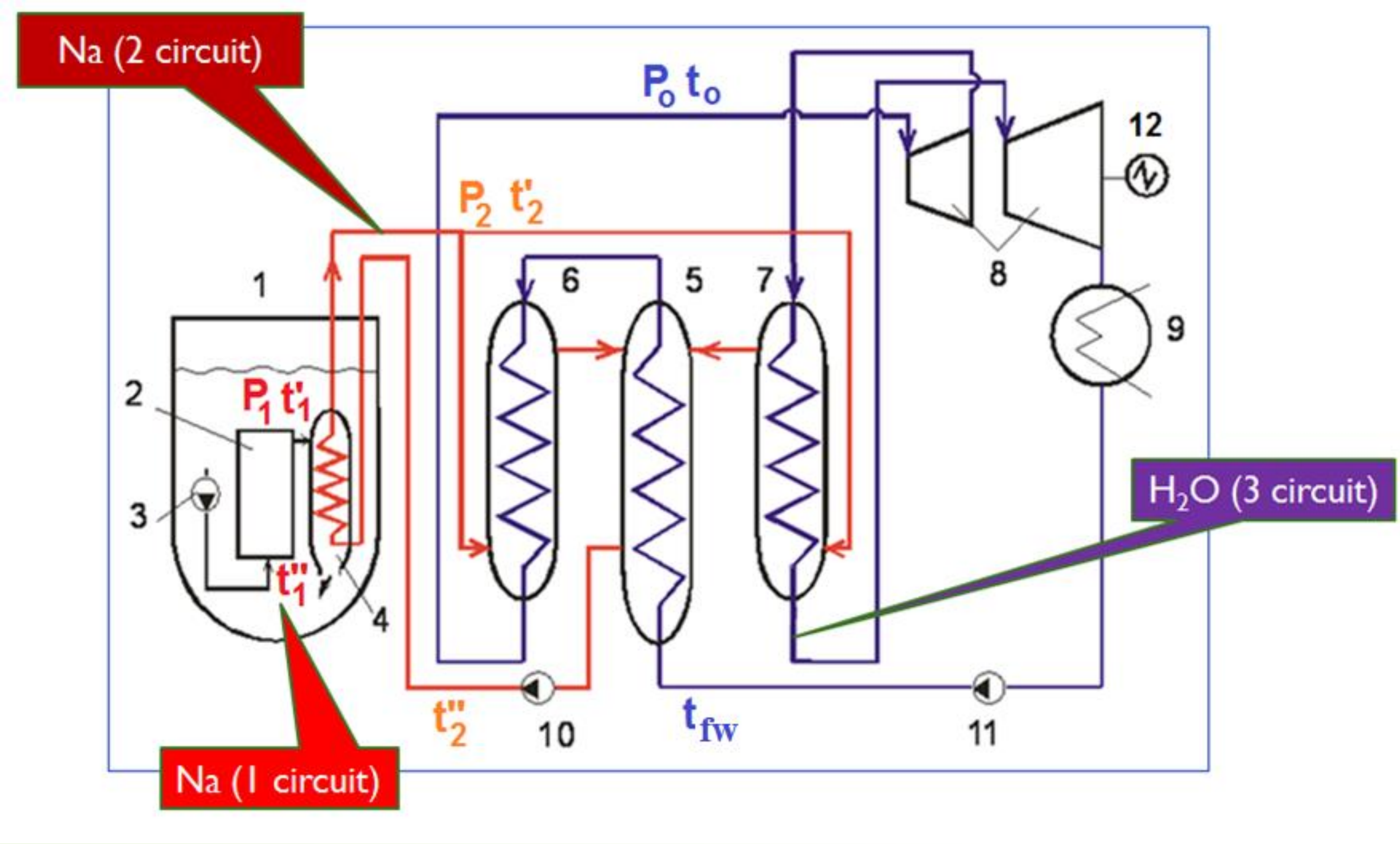
$$h_c = \frac{h_{fw} + \left(k_c - 1\right) \cdot h_2'}{k_c}$$

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

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, °C/°C	450/320	520/450	520/450
- working fluid inlet/outlet, °C/°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/(m²·K)	2410 4470 1720	1380	530

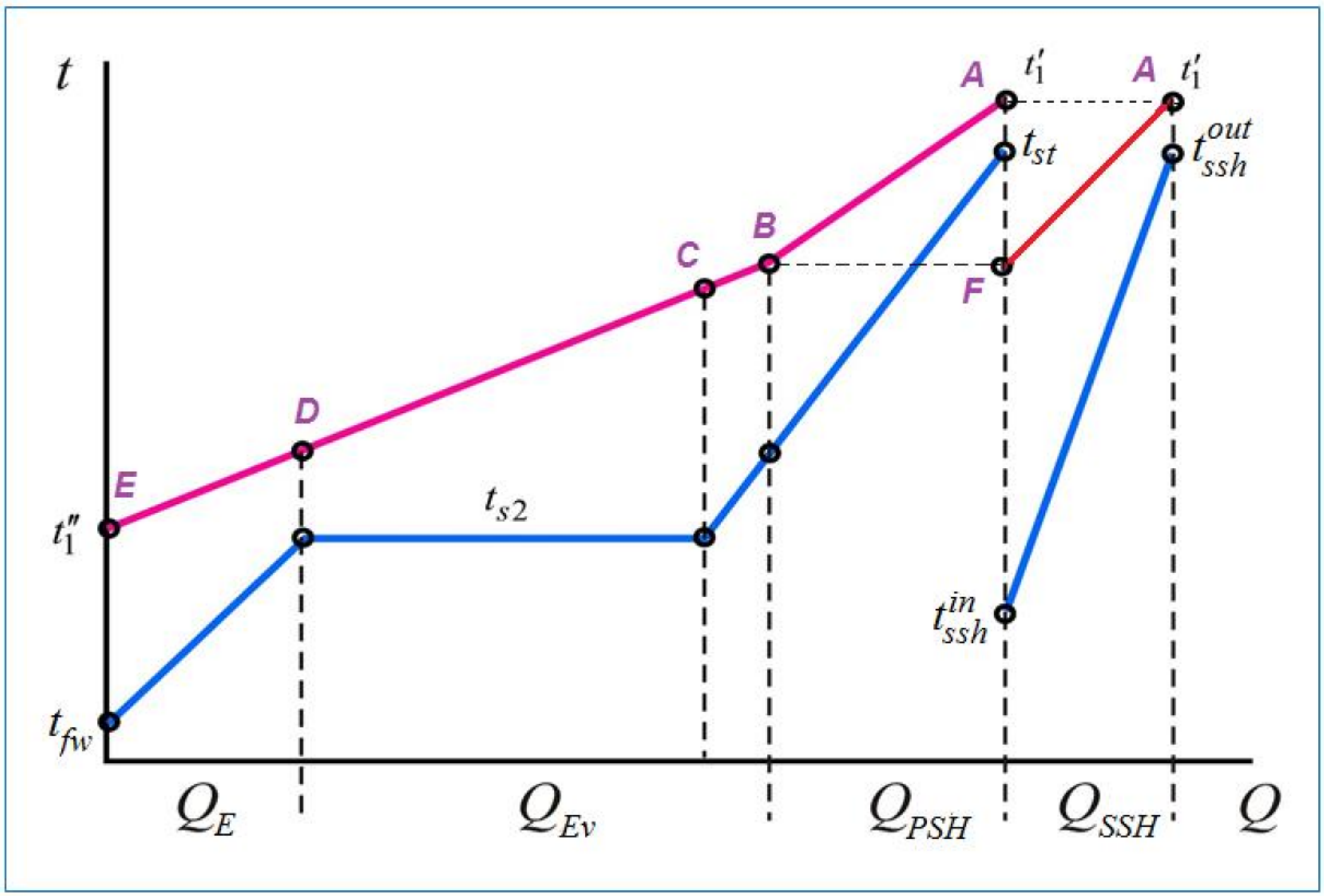


Fig. tQ- diagram of superheated steam generator with LMC (SG BN-600)

Characteristic temperatures on tQ - diagram

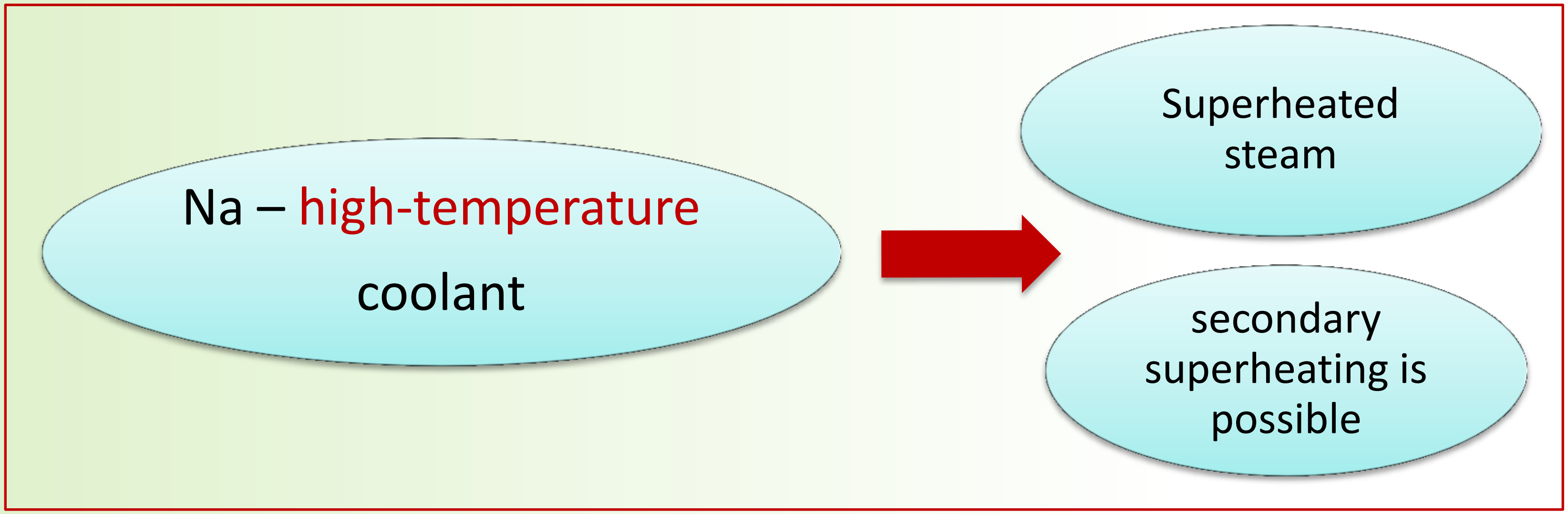
- t'_1 – coolant temperature at SG inlet;
- t''_1 - coolant temperature at SG outlet;
- t_{st} – temperature of generated steam in SG;
- t_{s2} – saturation temperature at pressure p_2;
- t_{fw} – feedwater temperature;
- Δt_r – water heating in reactor

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

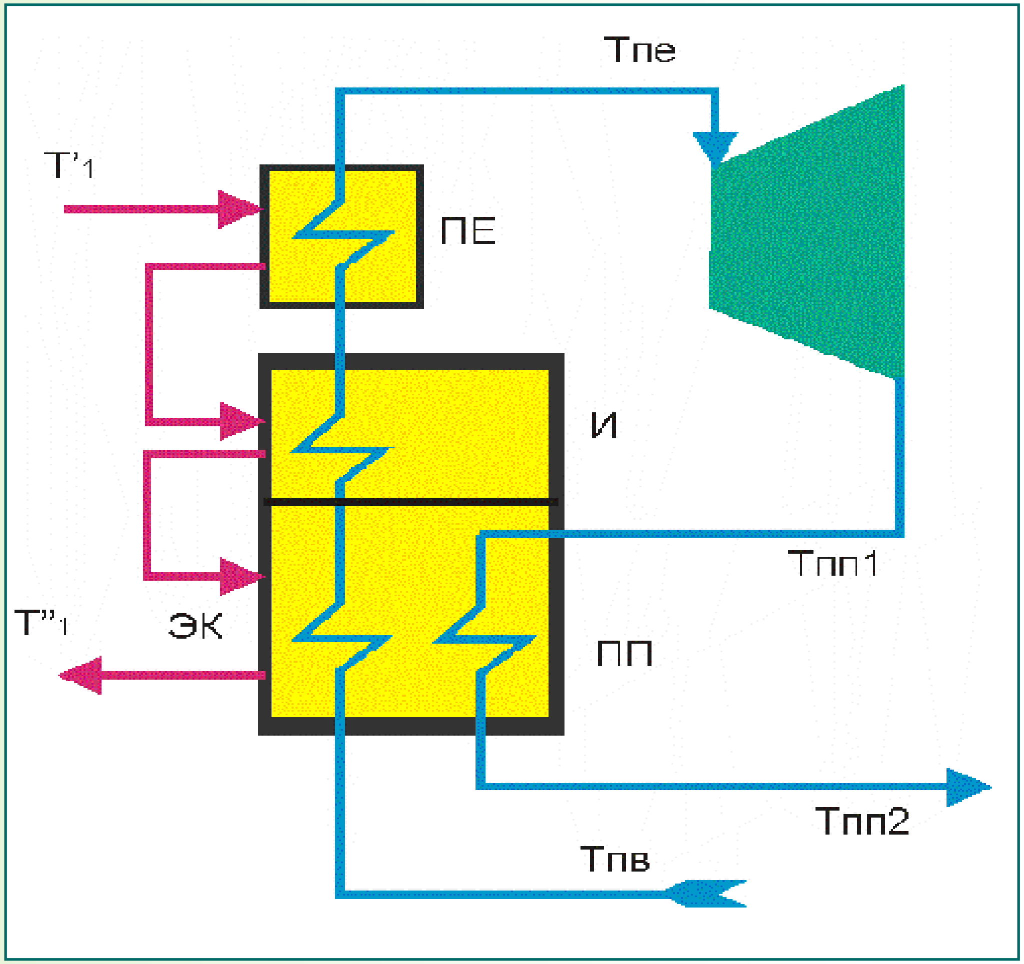
Cycle arrangements of SGs heated by liquid metal coolants



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



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

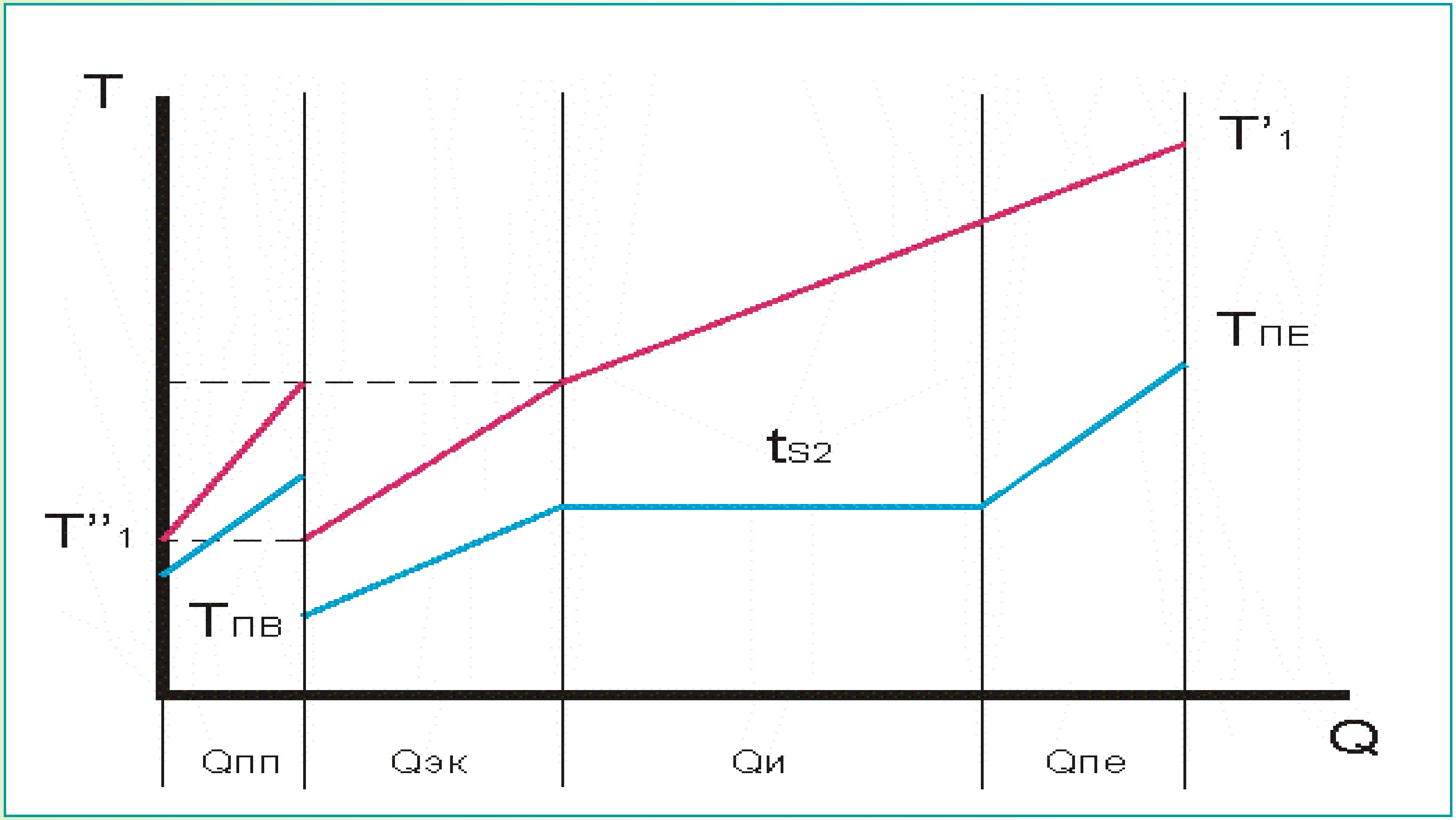


Fig. TQ-diagram for LMC SG with low-temperature secondary superheating

Thank you for attention