NPP STEAM GENERATORS

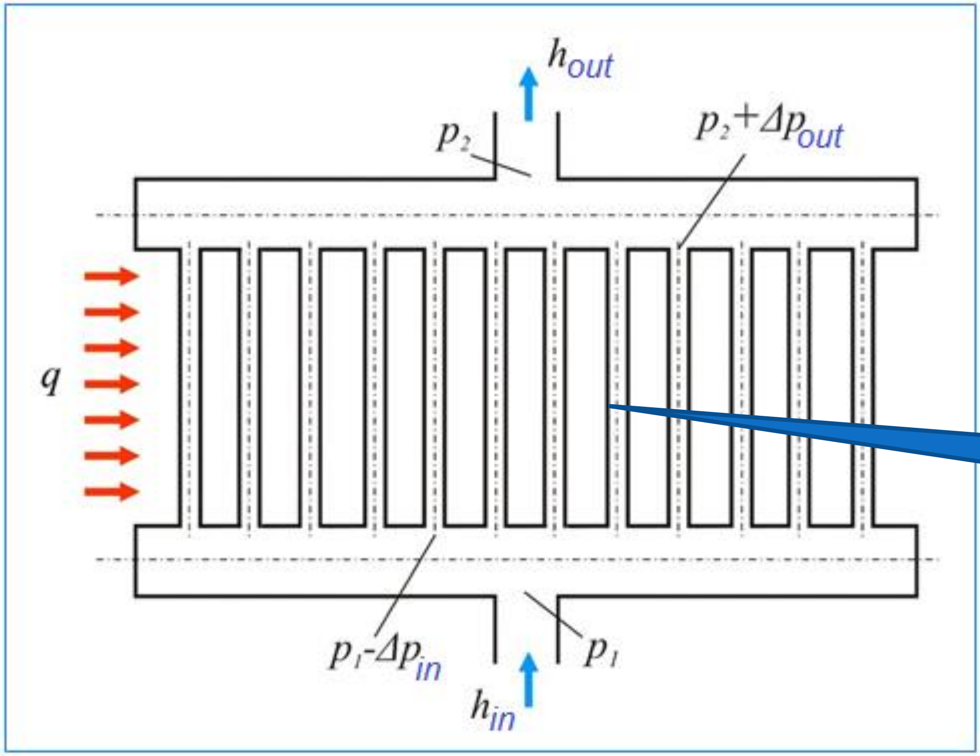
Operating conditions of heating surface with forced working fluid flow

Lecture outline

1. Thermal maldistribution (tube-to-tube temperature imbalance):
   - ✓ thermal and hydraulic non-uniformity;
   - ✓ ways to prevent thermal maldistribution
2. Thermal - hydraulic instability:
   - ✓ types of instabilities;
   - ✓ static instabilities;
   - ✓ dynamic instabilities

Thermal maldistribution

Thermal maldistribution



Heat transfer surface consists of parallel-channel heated tubes.

Heated water flows in tubes from bottom to top (upstream)

Heat exchange tubes

Here h_{in}, h_{out} – water enthalpy at the inlet and outlet of heat transfer surface;

Δp_{in}, Δp_{out} – pressure drops at the inlet and outlet of tubes

Thermal maldistribution

Enthalpy rise for a tube operating under average conditions, J/kg

$$\Delta h_{av} = \frac{q_{av} \cdot S_{av}}{D_{av}}$$

Enthalpy rise for an individual tube, J/kg

$$\Delta h_{t} = \frac{q_{t} \cdot S_{t}}{D_{t}}$$

Here q – heat flux density, W/m²;
S - heat transfer surface area of an individual tube, m²;
D – flow rate of water passing through an individual tube, kg/s

Thermal maldistribution

It is impossible to ensure constant flow rate of the medium for all tubes. Thus, different variants can be found for individual tubes:

$$\Delta h_t = \Delta h_{av}$$

$$\Delta h_t > \Delta h_{av}$$

$$\Delta h_t < \Delta h_{av}$$

Definition of «thermal maldistribution»

Nonidentity of heat transfer surface tubes with regard to enthalpy rise is called thermal maldistribution η

$$\eta = \frac{\Delta h_t}{\Delta h_{av}}$$

$$\eta = \frac{q_t \cdot S_t}{D_t} \cdot \frac{D_{av}}{q_{av} \cdot S_{av}} = \frac{q_t}{q_{av}} \cdot \left(\frac{D_t}{D_{av}} \right)^{-1} = \eta_T \cdot \eta_H^{-1}$$

The formula above comprises two ratios

$$\eta_T = \frac{q_t}{q_{av}}$$ - *thermal non-uniformity;*

$$\eta_H = \frac{D_t}{D_{av}}$$ - *hydraulic non-uniformity*

There is no thermal maldistribution if:

$$1)\ \eta_T = 1 \quad u \quad \eta_H = 1;$$

$$2)\ \eta_T = \eta_H$$

Problems that occur under thermal maldistribution conditions

If $\Delta h_t > \Delta h_{av}$ in economizers, some tubes operate at medium temperature exceeding the design temperature.

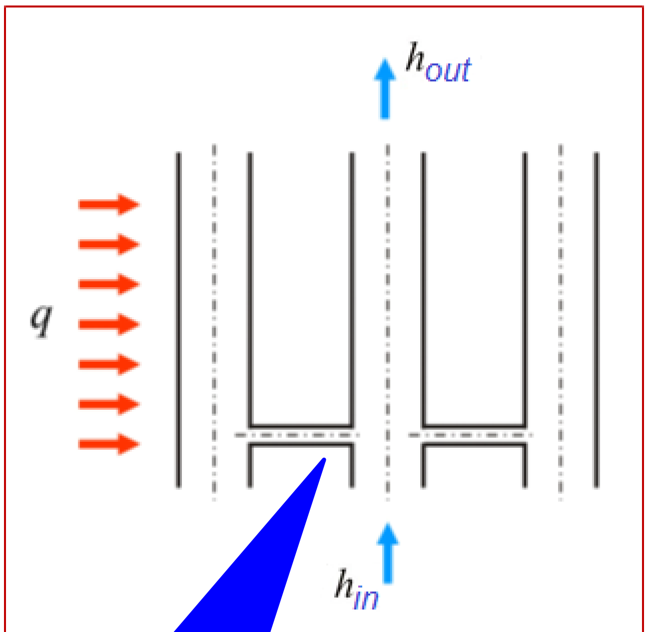
In this case the tube wall temperature may exceed the permissible temperature

$$t_{wall} < t_{wall}^{perm}$$

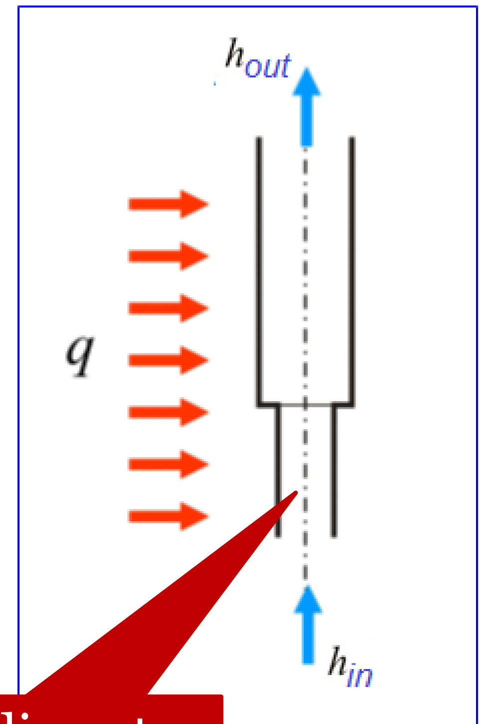
If $\Delta h_t > \Delta h_{av}$ in evaporators, transition of some tubes into the impaired heat transfer mode is possible

$$x_{out} > x_{bnd}$$

Ways to prevent thermal maldistribution

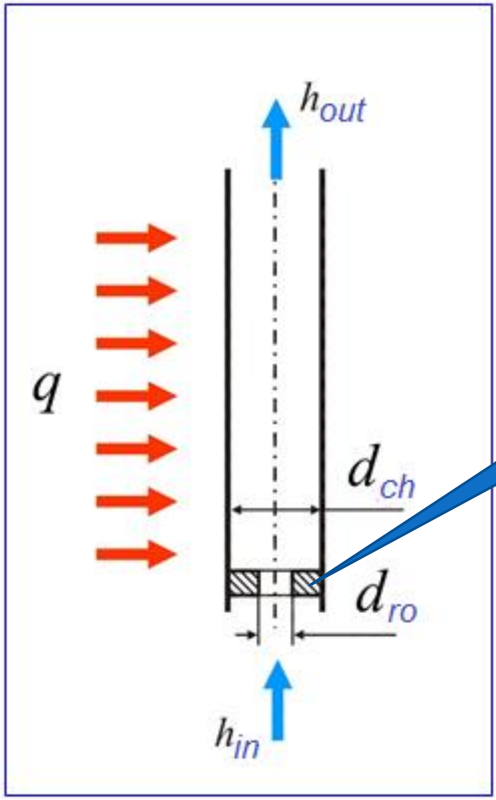


balancing headers



Variable diameter of the tube

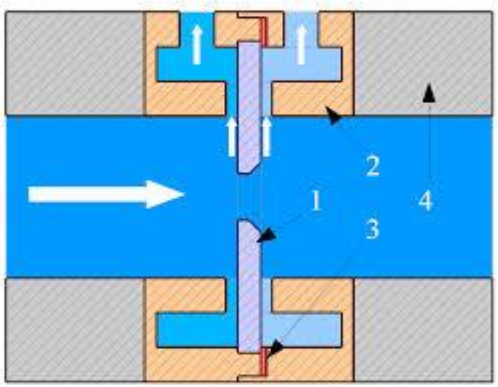
The main method for the prevention of tube-to-tube temperature imbalance is to install orifices on all the tubes



Restricting orifice

Here d_{ch} – channel (tube) diameter;
d_{ro} - orifice diameter

Restricting orifice



Thermal-hydraulic instability

Definition of thermal-hydraulic instability

Periodic or multiple change in thermal-hydraulic parameters of the flow in separate channels or in circulation loop at stationary operating conditions of the setup is known as flow instability.

Types of instabilities

Type	Manifestation pattern	Cause
Main static instability (Ledinegg type)	Sudden change in flow rate towards a new steady value	Different pattern of the ratio $\Delta P = f(G)$
Complex dynamic instability (turn-to-turn pulsation)	Redistribution of flow rates in parallel channels	Interaction of G, x, ΔP
Complex dynamic instability (general pulsation in evaporator)	Periodic change in total flow rate in the circuit	Unstable operation of the ‘heat exchanger-pump’ system

Main static instability (Ledinegg type)

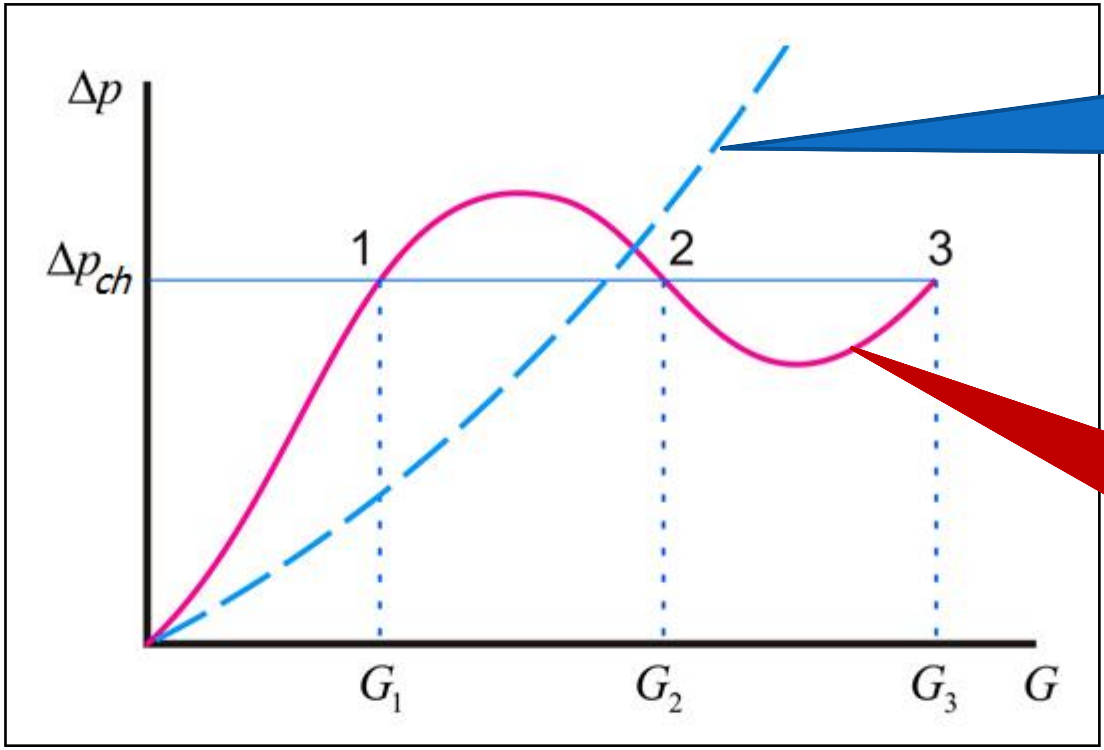
Disturbance of uniform distribution of the fluid in parallel channels (tubes) may be caused by 2 reasons:

- hydraulic non-uniformity $\eta_H \neq 1$;
- ambiguity of the channel's hydrodynamic characteristics (HDC)

$$\Delta p_{ch} = f(G)$$

$$\Delta p_{ch} = p_{in} - p_{out}$$

Static hydraulic characteristics of channel



Unambiguous HDC: one value of Δp_{ch} – one flow rate G

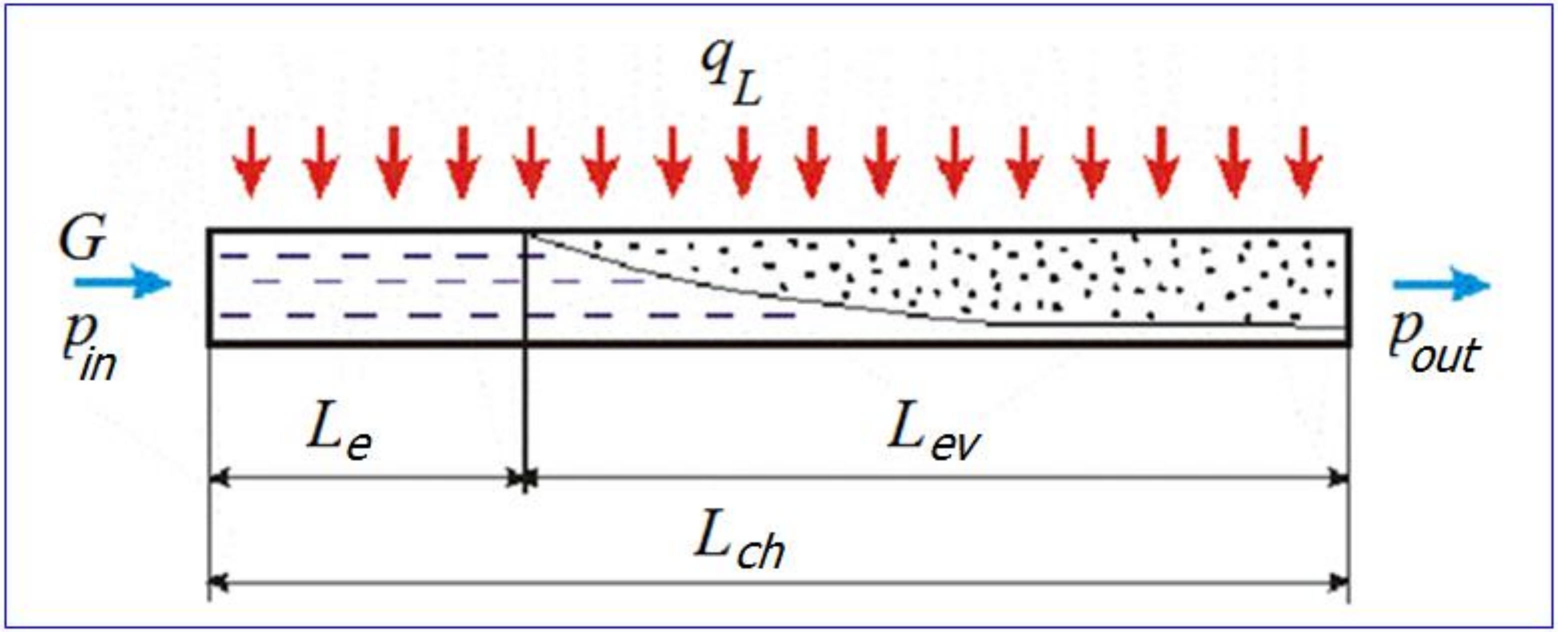
Ambiguous HDC: one value of Δp_{ch} – three flow rates G_1, G_2, G_3

Here $\Delta p_{ch} = p_{in} - p_{out}$ – pressure differential in the channel;
p_{in}, p_{out} – channel inlet and outlet pressures;
G - mass flow rate

Factors that affect flow instability

1. Subcooling to saturation at the inlet Δh_E
2. Flow direction (upstream, downstream)
3. Pressure
4. Local resistances

Schematic of a steam-generating tube (channel)



Here q_L - linear heat flux, W/m;
L_{ch} – channel length, m;
L_e , L_{ev} – length of economizing and evaporation zones, m;
p_{in} , p_{out} – pressure at the channel inlet and outlet

Derivation of HDC equation

Main assumptions:

- steam-generating channel consists of economizing and evaporation zones;
- linear heat flux q_L= const;
- specific volume in evaporation zone is equal to specific volume of saturated water $\upsilon_{ev}=\upsilon'$

Here HDC is hydrodynamic characteristics of the channel

$$\Delta p_{ch} = f(G)$$

$$\Delta p_{ch} = p_{in} - p_{out}$$

Derivation of HDC equation

$$\Delta p_{ch} = \Delta p_e + \Delta p_{ev}$$

$$\Delta p_{ch} = \xi \cdot \frac{L_e}{d_{ch}} \cdot \frac{G^2 \cdot \nu'}{2 \cdot f_{ch}^2} + \xi \cdot \frac{L_{ch} - L_e}{d_{ch}} \cdot \frac{G^2 \cdot \nu_{mix}}{2 \cdot f_{ch}^2}$$

Additional ratios:

$$f_{ch} = \frac{\pi \cdot d_{ch}^2}{4} \qquad w = \frac{G}{f_{ch} \cdot \rho} \qquad \Delta p = \xi \cdot \frac{L}{d_{ch}} \cdot \frac{\rho \cdot w^2}{2}$$

Derivation of HDC equation

$$L_e = \frac{G \cdot \left(h' - h_{in}\right)}{q_L} = \frac{G \cdot \Delta h_{in}}{q_L}$$

$$\nu_{mix} = \frac{\nu' + x \cdot \left(\nu'' - \nu'\right)}{2}$$

$$x = \frac{q_L \cdot \left(L_{ch} - L_e\right)}{G \cdot \left(h'' - h'\right)}$$

HDC equation

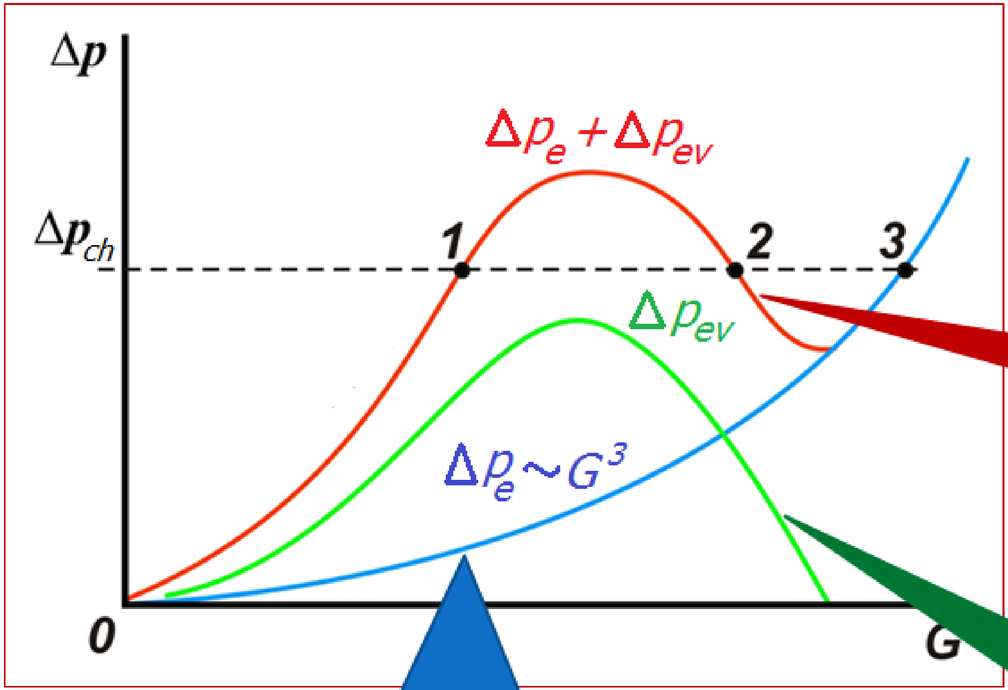
$$\Delta p_{ch} = A \cdot G^3 - B \cdot G^2 + C \cdot G$$

$$A = \frac{\xi \cdot \left(\nu'' - \nu'\right) \cdot 2 \cdot \Delta h_{\mathrm{in}}^2}{4 \cdot f_{ch}^2 \cdot d_{ch} \cdot q_L \cdot r}$$

$$B = \frac{\xi \cdot L_{ch}}{2 \cdot f_{ch} \cdot d_{ch}} \cdot \left[\frac{\Delta h_{in}}{r} \cdot \left(\nu'' - \nu'\right) - \nu' \right]$$

$$C = \frac{\xi \cdot \left(\nu'' - \nu'\right) \cdot L_{ch}^2 \cdot q_L}{4 \cdot f_{ch}^2 \cdot d_{ch} \cdot r}$$

Physical causes of non-uniformity



Pressure differential in the channel

Pressure differential in the economizer zone

Pressure differential in the evaporation zone

Physical causes of non-uniformity

The emergence of non-uniformity is explained by the effect of zone lengths L_e and L_{ev}:

- ❖ length of the economizer zone L_e rises proportionally with an increasing flow rate G;
- ❖ on the other hand, increasing flow rate G results in decreasing length of the evaporation zone L_{ev}.

Thus, resistance of the evaporation zone Δp_{ev} depends on medium flow rate G in a *complex* way.

All this leads to ambiguity of the channel's static hydraulic characteristics.

Condition for HDC unambiguity

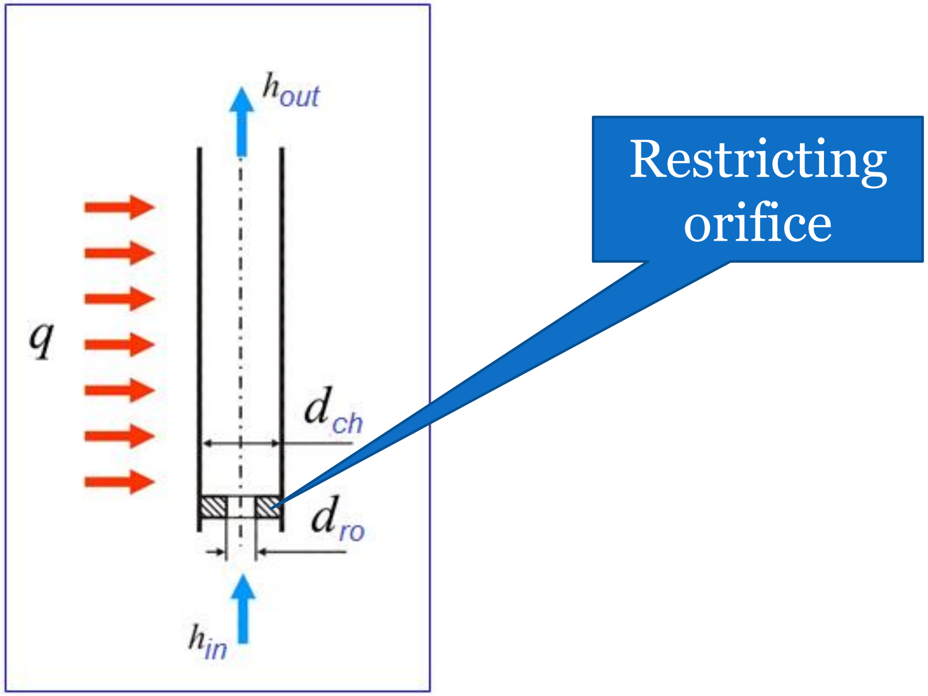
$$\left(\Delta h_{in}/r\right)\cdot\left(\rho'/\rho''-1\right)\leq B$$

- at B>7.5 – ambiguous HDC;
- at B≈7.5 – unambiguous HDC, but with plateau;
- at B≤5 – unambiguous HDC that fulfill the requirement for hydrodynamic stability

Here Δh_{in} - medium subcooling to saturation temperature;
$r=h'' - h'$ – latent evaporation heat;
ρ', ρ'' – density of saturated water and steam

Practical measures to fight instability

The main method for the prevention of thermal maldistribution is to install orifices for all inlet regions of the channels



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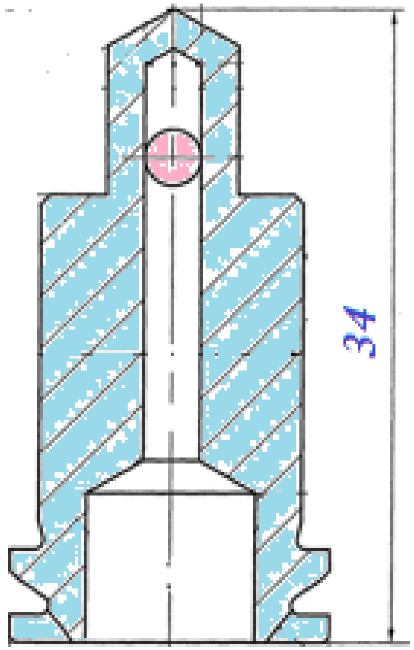
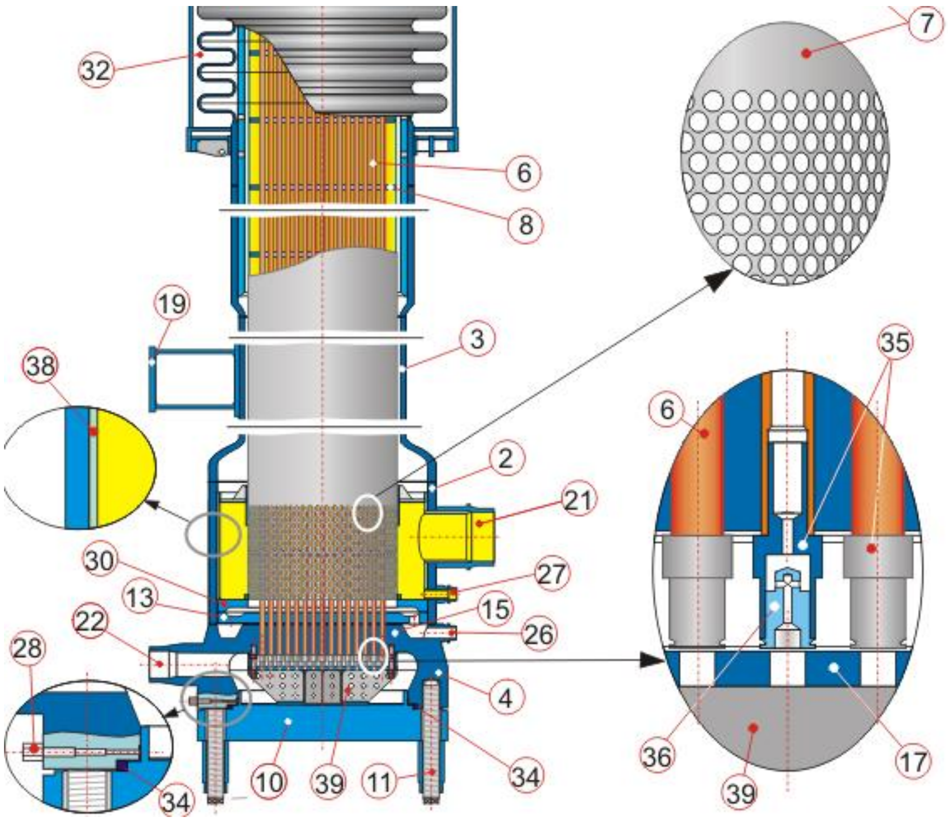


Practical measures to fight instability



17. Lower hold-down plate.
18. Upper support.
19. Intermediate support.
20. Coolant inlet pipe.
21. Coolant outlet pipe.
22. Feedwater inlet pipe.
23. Steam outlet pipe.
24. Reaction products discharge pipe.
25. Gas blow-off nozzle.
26. Coolant drain pipe on water chamber.
27. Coolant drain pipe on coolant outlet chamber.
28. Feedwater drain nozzle.
29. Upper pressing ring.
30. Lower pressing ring.
31. Lens expansion joint.
32. Expansion bellows shroud.
33. Packing diaphragm.
34. Sealing gasket (plate-type).
35. Throttle system nozzle Throttle (orifice).
36. Throttle (orifice).
37. Heat-exchange tube insert.
38. Thermal protection of vessel chambers.
39. Distribution the device.

Thank you for attention