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)

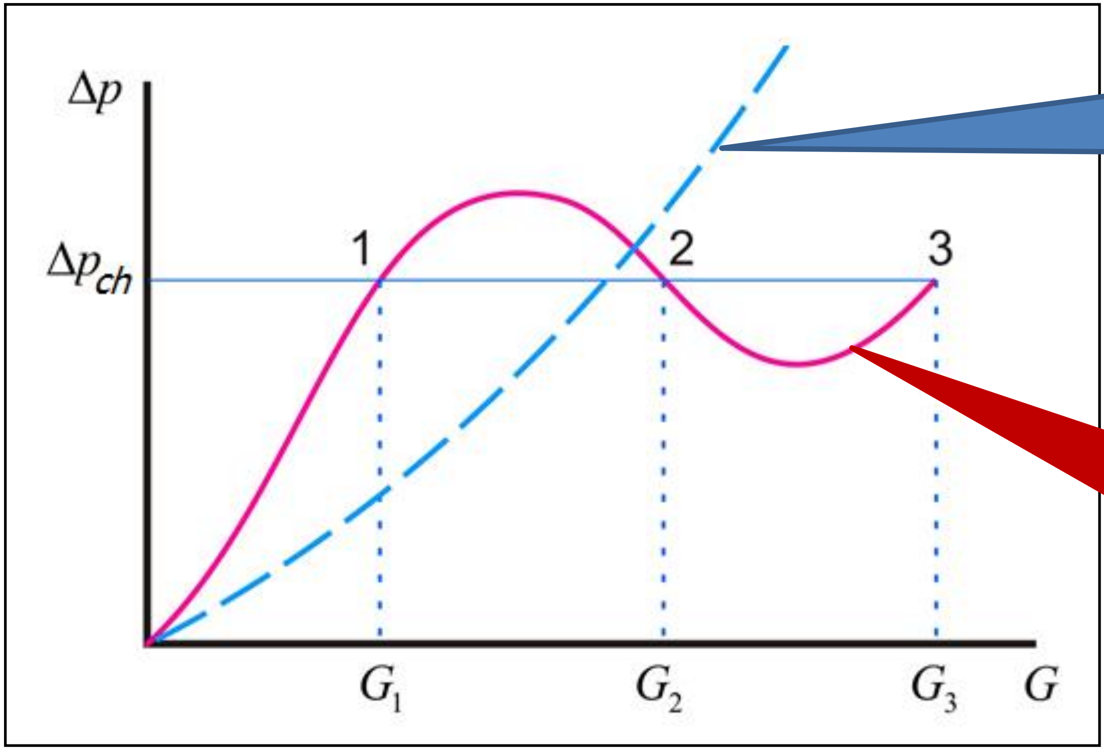
Disturbance of uniform distribution of the fluid in parallel channels (tubes) may be caused by 2 reasons:

- 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

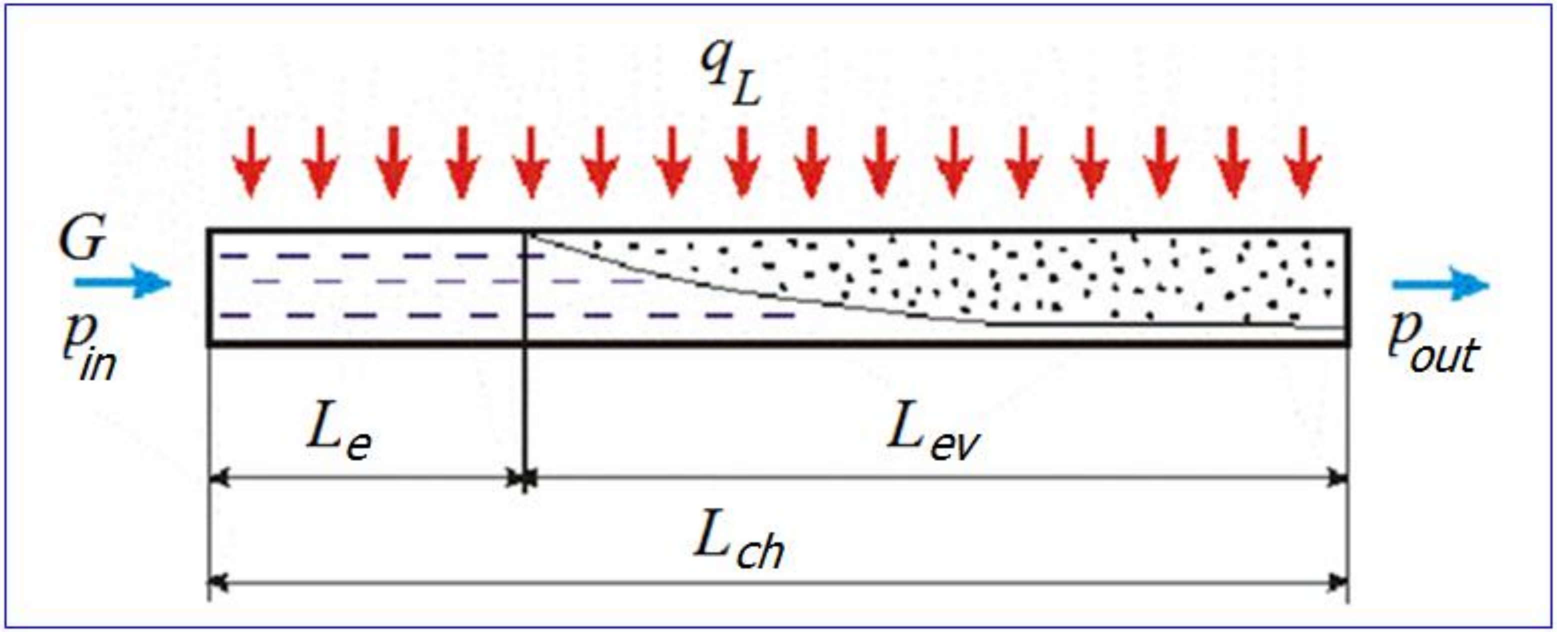
Ambiguous HDC:
one value of Δp_{ch} – three flow rates G_1, G_2, G_3

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 $\Delta h_{э}$
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 $v_{ev}=v'$

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

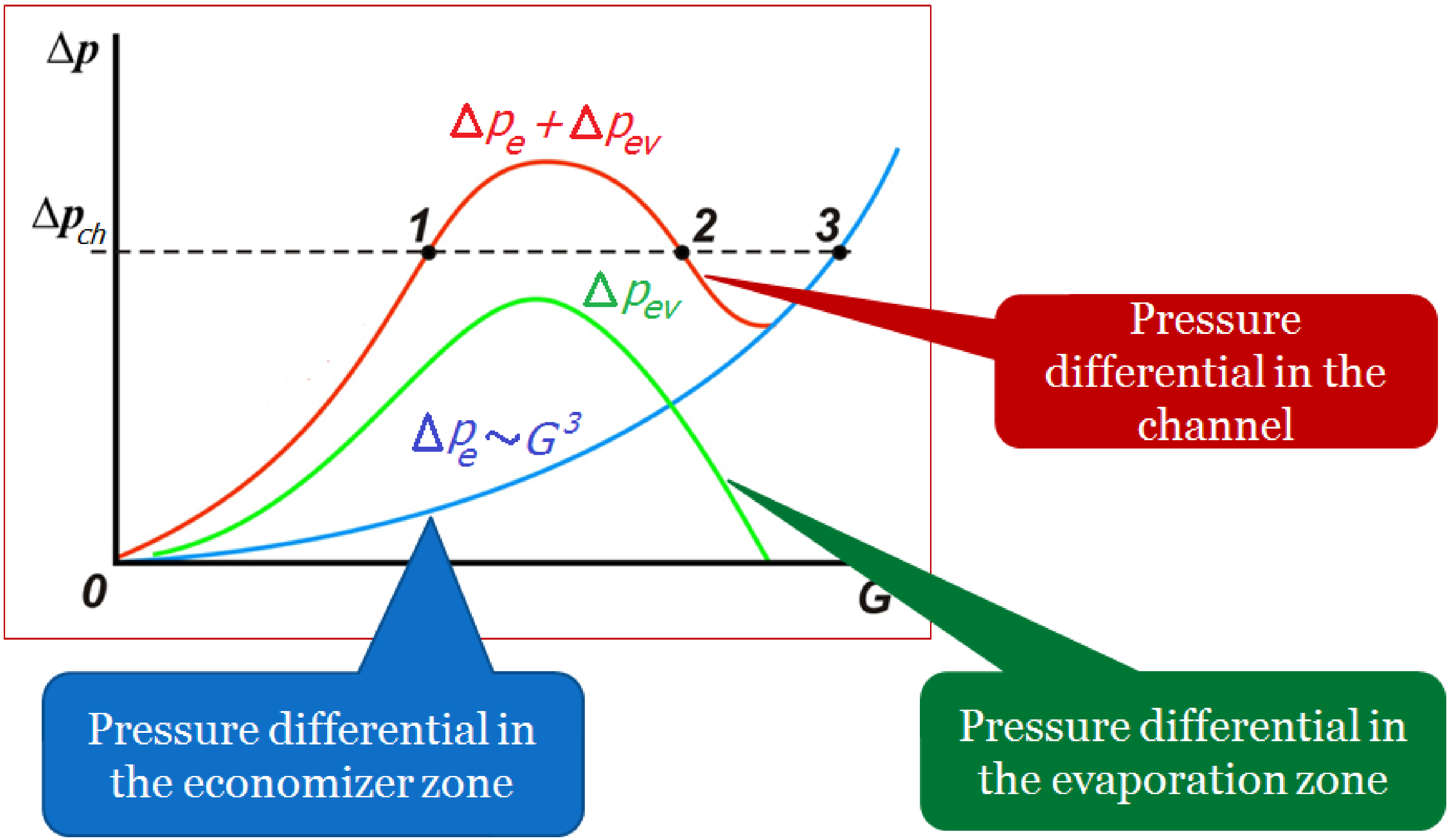
$$\Delta p_{ch} = A \cdot G^3 - B \cdot G^2 + C \cdot G$$

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

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

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

Physical causes of non-uniformity



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

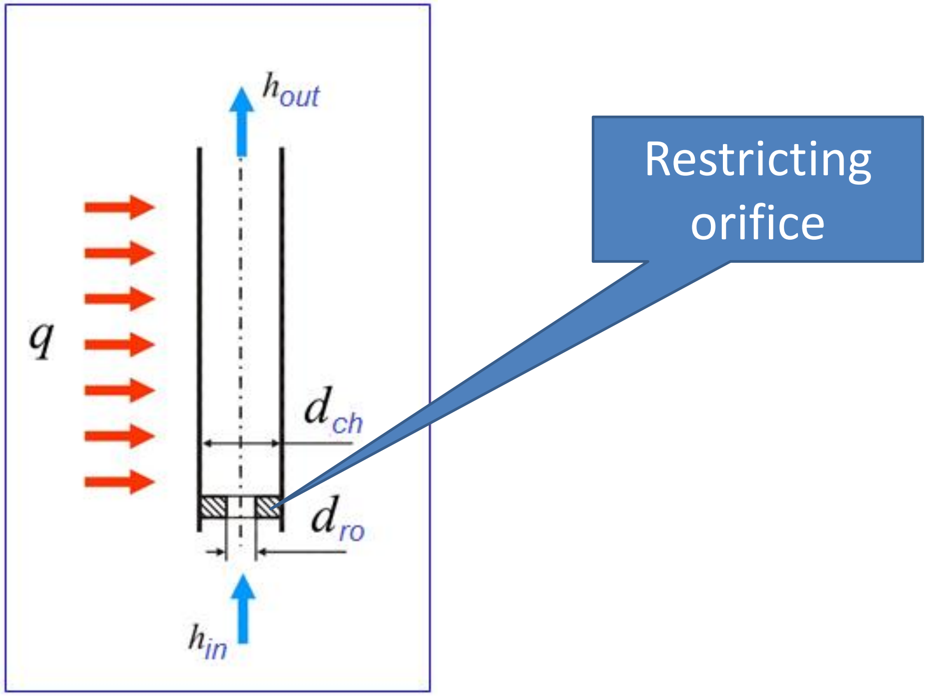
$$\left(\Delta h_{in}/r\right)\cdot\left(\rho'/\rho''-1\right)\leq B$$

- at $B>7.5$ – ambiguous HDC;
- at $B\approx7.5$ – unambiguous HDC, but with plateau;
- at $B\leq5$ – 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



Thank you for attention