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NPP STEAM GENERATORS

Theme. Hydrodynamic processes in SG.

Pressure drop for single-phase coolant flow

Lecture plan

1. NPP SG hydrodynamic problems
2. Determining factors
3. General scheme for pressure drops (losses) calculation
4. Pressure drop for single-phase fluid flow

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Hydrodynamic issues of NPP SGs

Service reliability of NPP SGs is associated in many respects with hydrodynamic processes of coolants and working fluids.

There are no SGs that do not exploit the movement of fluids or gases to transport and transfer heat energy from the coolant to the working fluid.

Hydrodynamic processes determine the level and stability of the temperature pattern in the assembly parts of SGs.

These processes can also be the reason of vibration, erosive damage, force impact on the construction elements of SGs, etc.

Hydrodynamic issues of NPP SGs

Development of nuclear power industry is impossible without an in-depth study of hydrodynamics and heat transfer processes.

Meanwhile, the most important is the investigation into various parameters with regard to steam-water mixture.

The study of single-phase medium hydrodynamics is of considerable importance for nuclear power plants where water, liquid metals, and gases are used as coolants.

Enhancement of efficiency and reliability of power equipment requires increased calculation accuracy.

Hydrodynamic issues of NPP SGs

On the one hand, the intensity of heat transfer in a SG is determined by a heat surface geometry, thermal and physical properties of a substance at the set parameters, and especially by the hydrodynamics of the flow.

On the other hand, the hydrodynamic processes determine the efficiency of a SG since the heat transfer efficiency and the power input needed for circulation are dependent on the organization of coolants' movement.

Hydraulic calculation along with thermal calculation are the primary calculations when designing a SG.

Hydrodynamic issues of NPP SGs

The main objective is to determine the pressure drop at medium flow (with given flow rate, with account of parameters and selected constructional dimensions).

Additional tasks:

- to calculate the distribution of flow rates and velocities of the medium;
- to analyze the thermal hydraulic stability, etc.

Main determining factor

Flow structure (*motion mode*):

- for a single-phase medium – turbulent or laminar flow (analytical and empirical dependences);

- for a two-phase medium – flow regimes (not less than 5-8) (empirical dependences)

General scheme for pressure drop calculation

Overall resistance in the separate sections for each SG passage/channel (coolant, working fluid) is defined as

$$\Delta p_{ov} = \Delta p_{in} + \Delta p_{trs} + \Delta p_{out} \qquad (1)$$

where $\Delta p_{полн}$ is overall resistance of the passage (channel) of coolant or working fluid;

Δp_{in}, Δp_{out} is the resistance in the inlet and outlet sections;

Δp_{trs} is the resistance of the heat transfer surface

General scheme for pressure drop calculation

Any summand of the formula (1) can be defined as

$$\Delta p = \Delta p_h + \Delta p_{spd} + \Delta p_{acc}$$

where $\Delta p_{hP} = \Delta p_{fr} + \Sigma \Delta p_{loc}$ is the hydraulic pressure drop in the channel;

Δp_{fr} – pressure drop due to friction;

Δp_{loc} – pressure drop across local resistances;

Δp_{spd} - static pressure difference (difference pressure due to vertical rise or fall of fluid);

Δp_{acc} - pressure drop due to flow acceleration

Hydraulic resistance of heat exchange surface (tubes, longitudinal-flow tube banks)

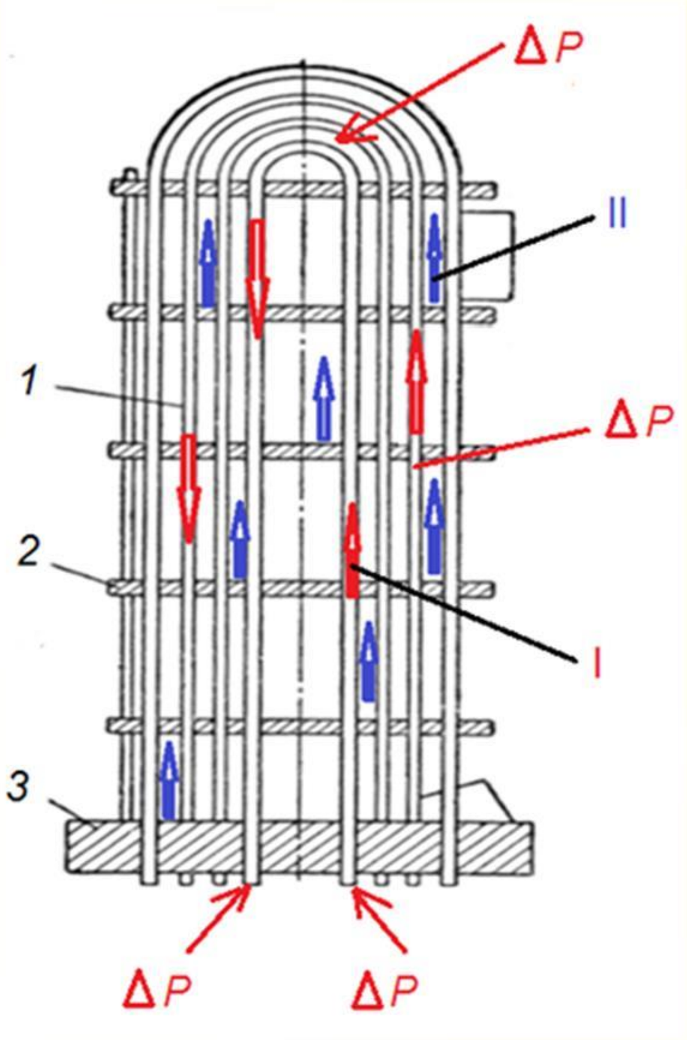


Fig. Calculation scheme

1 – heat exchange tubes;

2 – tube supports;

3 – tube sheet;

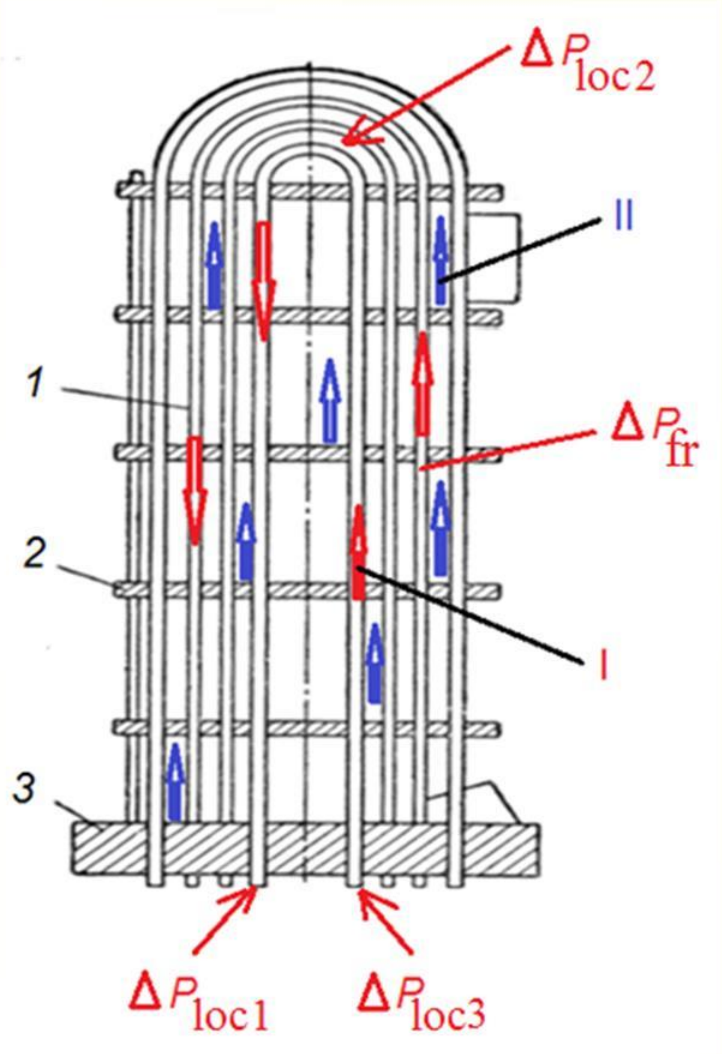
I – coolant channel(tubes);

II – working fluid annulus/channel (intertubular space)

General equation

$$\Delta p_h = \Delta p_{fr} + \Sigma \Delta p_{loc}$$

Hydraulic resistance of heat exchange surface (tubes, longitudinal-flow tube banks)



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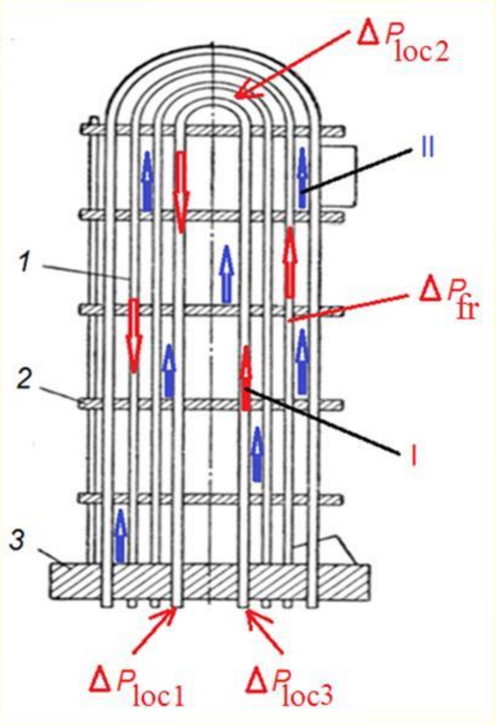
Example of calculation of heat exchange surface hydraulic resistance along the coolant channel

Coolant channel – heat-exchange tubes

$$\Delta p_h = \Delta p_{fr} + \Delta p_{loc1} + \Delta p_{loc2} + \Delta p_{loc3}$$

- frictional pressure drop
- inlet pressure drop
- pressure drop due to 180° turn
- outlet pressure drop

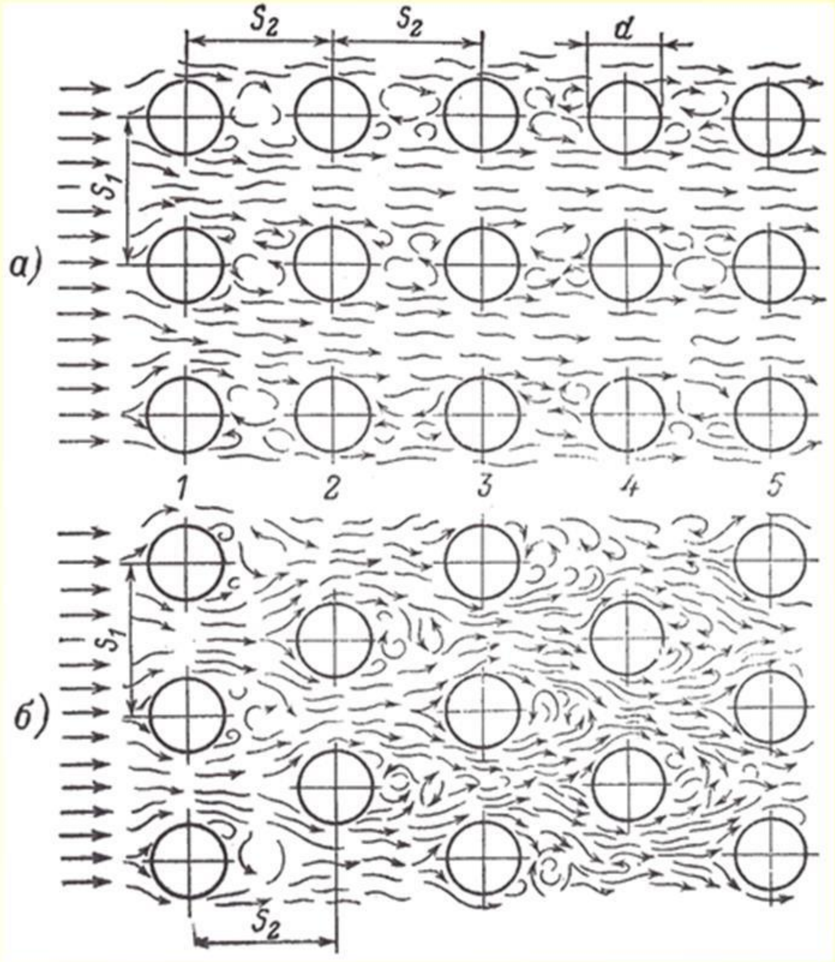


Hydraulic resistance of heat exchange surface (crossflow over tube bundle)

General equation

$$\Delta p_h = \Delta p_{cross}$$

Note. Pressure drops due to friction and local resistances are not distinguished



Calculation of pressure drop constituents in single-phase flow

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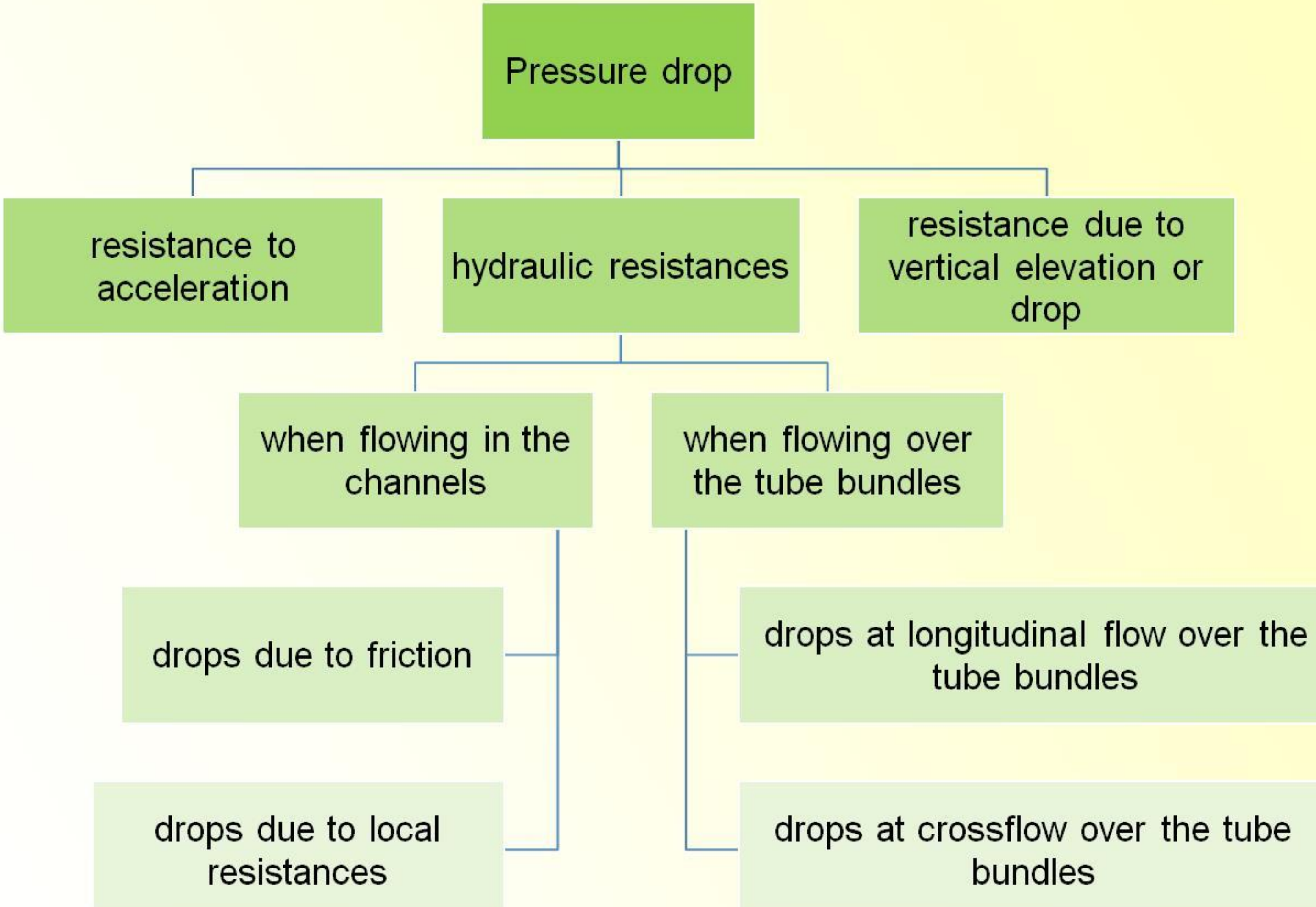
Formula selection algorithm for calculation of pressure drop in single-phase flow



Selection of optimum velocity

Factors that restrict the max velocity:

- increased hydraulic losses (rise in energy consumption needed for circulation);
- erosive wear;
- appearance of vibration.

Factors that restrict the min velocity:

- impaired (degraded) heat transfer process;
- danger of dead(stagnation) zones appearance;
- natural circulation disruption

Selection of optimum velocity

Recommended steam velocity:

- of high pressure (more than 9 MPa) 10…20 m/s;
- of medium pressure (less than 9 MPa) 20…30 m/s

Recommended coolant velocity:

- water 2…5 m/s ;
- LMC 1..3 m/s

Recommended working fluid velocity (water):

- forced circulation - 2…5 m/s;
- natural circulation – 0.5…1.2

Drop pressure due to friction

General equation:

$$\Delta p_{fr} = \xi \cdot \frac{L}{d_h} \cdot \frac{\rho \cdot w^2}{2} = \xi \cdot \frac{L}{d_h} \cdot \frac{G^2}{2 \cdot F^2 \cdot \rho}$$

Here ξ – friction factor;
w – characteristic velocity;
ρ – mean density of the medium;
L – channel length;
d_h – hydraulic diameter of the channel;
G – mass flow rate;
F – channel flow section area

Friction factors

Circular tubes, turbulent regime. Altshul formula

$$\xi_0 = 0{,}11 \cdot \left[\left(\Delta / d_h \right) + \left(68 / \mathrm{Re} \right) \right]^{0{,}25};$$

here d_h – hydraulic (inner) diameter;
Δ - equivalent roughness;
Re – Reynolds number

Notes. Data on equivalent roughness Δ:

- ✓stainless steel…$1 \cdot 10^{-5}$ m;
- ✓carbon steel….$8 \cdot 10^{-5}$ m, (new tubes);
- ✓carbon steel….$2 \cdot 10^{-4}$ m, (tubes with slight corrosion)

Reynolds number

- determines the fluid's hydrodynamic pattern

$$Re = \frac{w \cdot d}{\nu} = \frac{w \cdot d \cdot \rho}{\mu}$$

Critical Reynolds number

The laminar flow regime is characterized by the absence of pulsations of the hydrodynamic quantities.

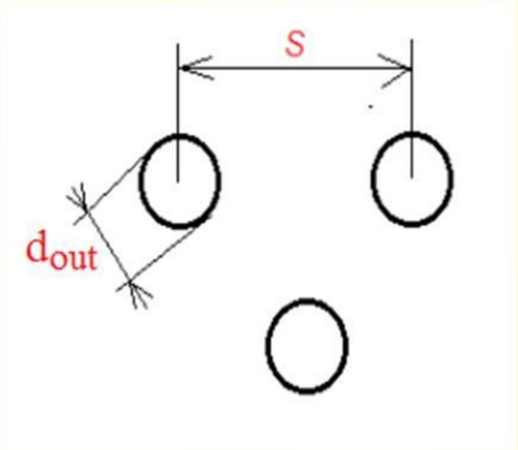
The critical Reynolds number Re_{cr} at which the laminar flow regime in the circular pipes is destroyed is usually taken to be 2300.

For other types of channels, Re_{cr} is given in the table

Channel type	Re_{cr}
Ring	2000…2800
Rectangular	2000…2300
Bundles of rods	≈2000

Friction factors

Bundles of circular rods



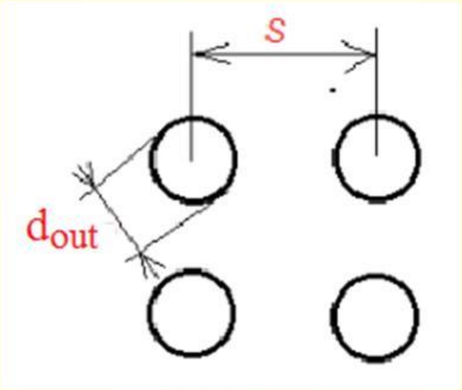
triangular arrangement

$$\xi = \frac{0,210}{\mathrm{Re}^{0.25}} \cdot \left[1 + (x-1)^{0.32} \right];$$

$$d_h = d \cdot \left(\frac{2 \cdot \sqrt{3}}{\pi} \cdot x^2 - 1 \right) \approx d \cdot \left(1,103 \cdot x^2 - 1 \right);$$

here d_h – hydraulic (equivalent) diameter of a tube bundle;
$x=S/d_{out}$ – relative bundle spacing;
S – absolute bundle spacing;
d_{out} – tubes' outer diameter

Friction factors



Bundles of circular rods

square arrangement

$$\frac{\xi}{\xi_0}=0.59+0.19\cdot(x-1)+0.52\cdot\left\{1-\exp\left[-10\cdot(x-1)\right]\right\};$$

$$d_h=d\cdot\left(\frac{4}{\pi}\cdot x^2-1\right)\approx d\cdot\left(1,27\cdot x^2-1\right)$$

here d_h – hydraulic (equivalent) diameter of a tube bundle;
$x=S/d_{outer}$ – relative bundle spacing;
S – absolute bundle spacing;
d_{outer} – outer diameter of tubes

Pressure drops due to local resistances

General equation

$$\Delta p_{loc} = \xi_{loc} \cdot \frac{\rho \cdot w^2}{2}$$

here ξ_{loc} – local resistance coefficient;
w – characteristic velocity;
ρ – mean density of the medium

Local resistance coefficients

Type of resistance	Formula
Sharp contraction (narrowing) of the flow cross section	$\xi_{loc} = 0{,}5 \cdot [\, 1 - F_S/F_L]$
Sharp enlargement (widening) of the flow cross section	$\xi_{loc} = 1{,}1 \cdot [\, 1 - (F_S/F_L)^2]$
Grid inside the tubes	$\xi_{loc} = \left[\left(1 + 0.707/\sqrt{1 - F_S/F_L}\right) \cdot \left(F_L/F_S - 1\right)\right]^2$
Turn at a 90-degree angle	$\xi_{loc} = 0.2 \ldots 0.41$
at a 180-degree angle	$\xi_{loc} = 0.26 \ldots 0.6$
Entrance or exit from the intertubular (annular) space	$\xi_{loc} = 1.5$
Entrance to the tubes from the collector	$\xi_{loc} = 0.5$
Exit from the tubes to the collector	$\xi_{loc} = 1.0$

Here F_S – smaller area; F_L – larger area

Pressure drop (cross flow over tube bundles)

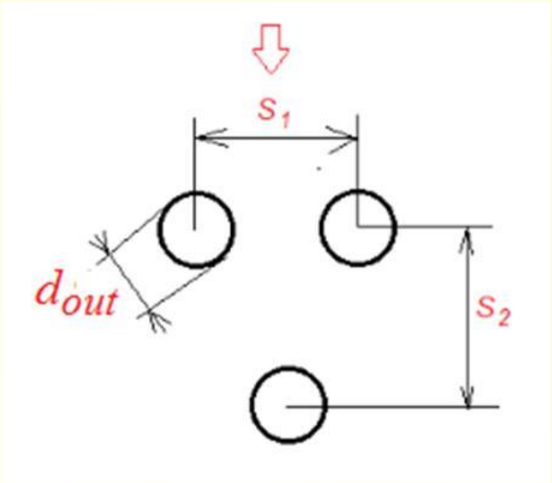
General equation

$$\Delta p_{cros} = \xi_{cros} \cdot \frac{\rho \cdot w^2}{2}$$

Here w – characteristic velocity;
ρ – mean density of the medium

Note. In case of cross flow over the tube bundles, total (cumulative) hydraulic resistance is calculated.

Pressure drop (cross flow over tube bundles)

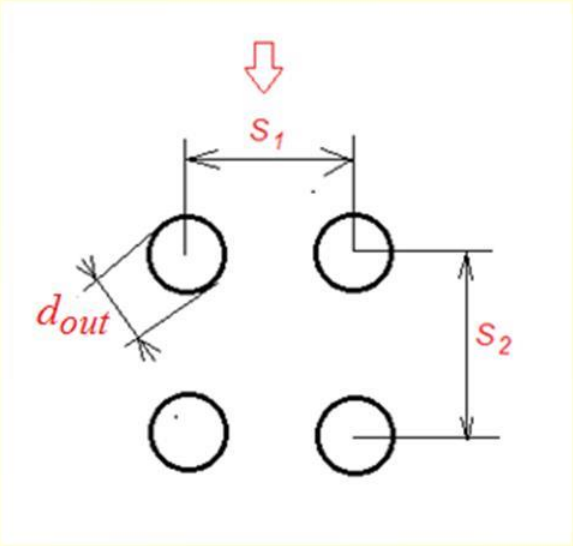


For staggered bundles

$$\xi_{cros}=\begin{cases}(4+6,6\cdot Z_2)\cdot \mathrm{Re}^{-0,28} & npu\ S_1<S_2\\(5,4+3,4\cdot Z_2)\cdot \mathrm{Re}^{-0,28} & npu\ S_1>S_2\end{cases}$$

Here Z_2 – number of rows along the flow direction

Pressure drop (cross flow over tube bundles)



For corridor tube bundles

$$\xi_{cros} = \left(6 + 9 \cdot Z_2\right) \cdot \mathrm{Re}^{-0,26} \cdot \left(S_1 / d_{out}\right)^{-0,23}$$

Here d_{out} – outer diameter of the tube

Pressure drop due to flow acceleration

$$\Delta p_{acc} = \rho_2 \cdot w_2^2 - \rho \cdot w_1^2$$

Here ρ_1 , ρ_2 – density of the medium in the beginning and at the end of the passage плотность среды в начале и конце тракта;

w_1 , w_2 – velocity of the medium in the beginning and at the end of the passage *скорость* среды в начале и конце тракта

Example

P_{fw}=13 MPa; t_{fw}=200 °C; ρ_{fw}=690 kg/m^3

P_{st}=13 MPa; t_{st}=500 °C; ρ_{st}=40.8 kg/m^3

$$\Delta p_{acc} = \rho_{st} \cdot \omega_{st}^2 - \rho_{fw} \cdot \omega_{fw}^2 = 40,8 \cdot 50^2 - 690 \cdot 3^2 \approx 0,096\ MPa$$

Pressure difference due to head loss (elevation or drop of channel height)

$$\Delta p_{spd} = g \cdot \sum \rho_i \cdot h_i$$

Here ρ_i – mean density of the medium in i-section;

h_i – height of the i-section

Pump power

$$N = V \cdot \frac{\Delta P_{ov}}{\eta} = G \cdot \frac{\Delta P_{ov}}{\rho \cdot \eta} = G \cdot \frac{\Delta P_{ov} \cdot \upsilon}{\eta}$$

Type of power unit	WWER-440	WWER-1000
η, %	50…70	60…77
Pump type	Main circulation pump 317 (GTSN-317)	Main circulation pump 195 (GTSN-195)

Thank you for attention