ТОМСКИЙ
ПОЛИТЕХНИЧЕСКИЙ
УНИВЕРСИТЕТ

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

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.

He most important is the study of various parameters of the 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.

Improving the efficiency and reliability of power equipment requires an increase in the accuracy of calculations.

РБ-040-09 «Calculated ratios and methods for calculating the hydrodynamic and thermal characteristics … of the water cooled reactors»

Коэффициент теплоотдачи при кипении в трубах воды, недогретой до температуры насыщения, рассчитывается по формуле [7]:

$$\alpha = 0{,}70\alpha_0\left\{1+\left[\frac{1}{0{,}7\alpha_0\left(\frac{1}{\alpha_1}-\frac{t_s-t_ж}{q}\right)}\right]^{3/2}\right\}^{2/3}, \qquad (3.2.2.29)$$

где α… рассчитывается по формуле (3.2.2.1);

… рассчитывается по формуле (3.2.1.10);

… $\frac{w_0 d_{вн}}{\nu}$ – при расчете α_1;

…скорость циркуляции воды, м/с;

…т/м^2;

…средняя температура воды в заданном с…нии трубы, °С;

$t_s - t_ж$ – недогрев воды до температуры нас…щения, °С.

Пределы применимости формулы:

$P = 0{,}10 \div 18$ МПа; $t_s - t_ж = 1 \div 260$ °С.

$\boxed{\text{Погрешность } \Delta \text{ расчета } \alpha \text{ составляет } \pm 30\%.}$

heat transfer coefficient at boiling in pipes

formula 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

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

where Δp_{ov} 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

ТОМСКИЙ
ПОЛИТЕХНИЧЕСКИЙ
УНИВЕРСИТЕТ

General scheme for pressure drop calculation

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

$$\boxed{\Delta p = \Delta p_{hpd} + \Delta p_{spd} + \Delta p_{acc}}$$

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

Δp_{fr} is pressure drop due to friction;

Δp_{loc} is pressure drop across local resistances;

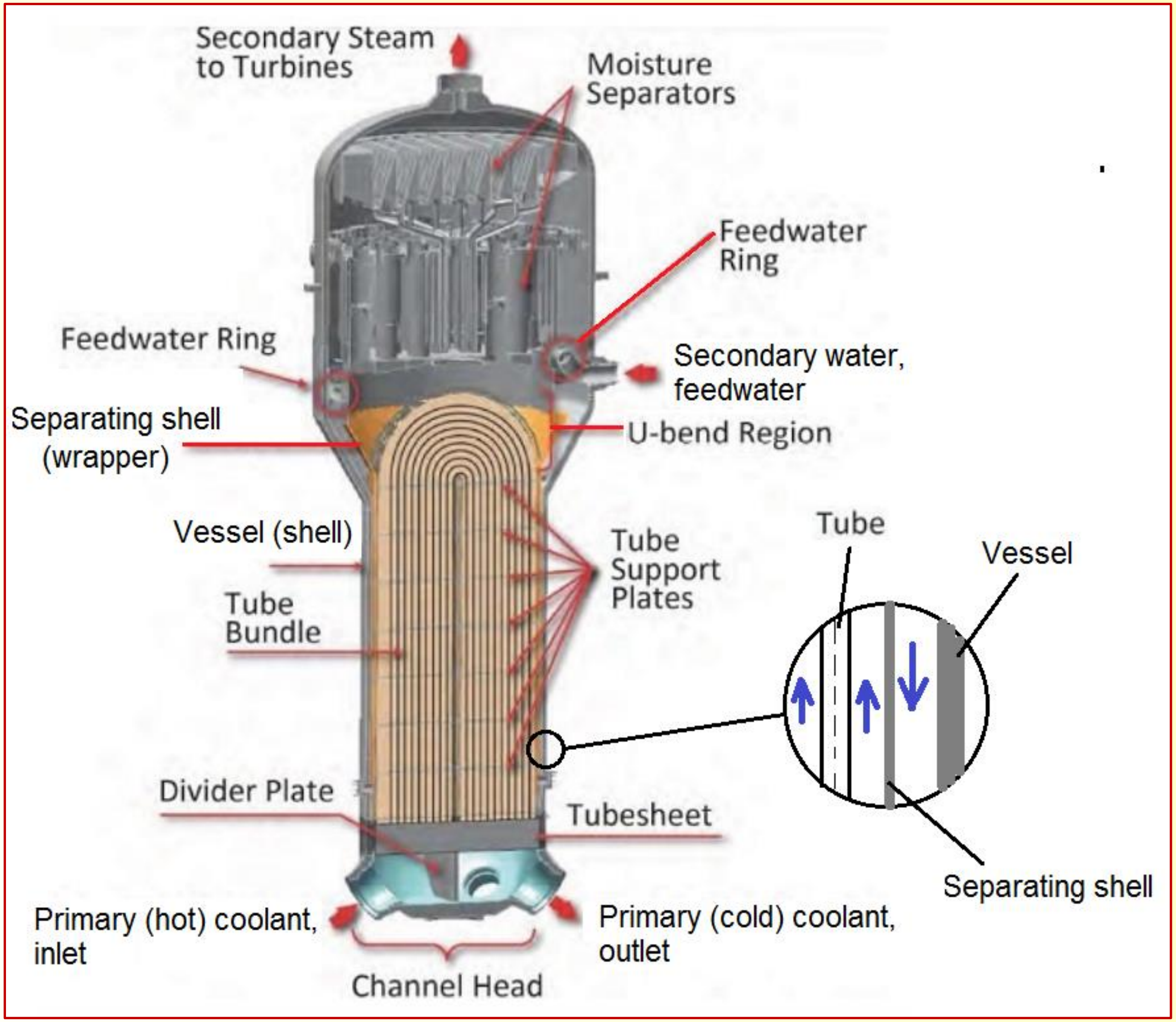
Δp_{spd} is static pressure difference (difference pressure due to vertical rise or fall of fluid);

Δp_{acc} is pressure drop due to flow acceleration

e.g. The flow diagram of the coolant in a vertical steam generator

The coolant moves inside the tubes. First up and then down

The working fluid moves between the tubes. Down near the walls of the vessel, up in the center.



ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

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

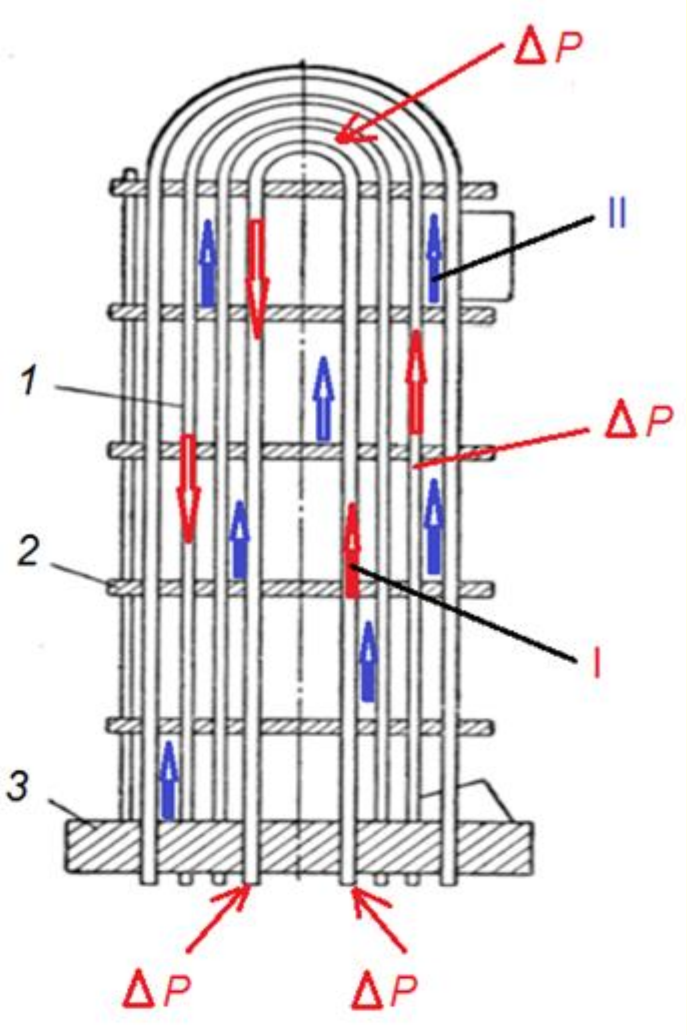


Fig. Calculation scheme

1 – heat exchange tubes;

2 – tube supports;

3 – tube sheet;

I – coolant channel(tubes);

II – working fluid channel (intertubular space)

General equation

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

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

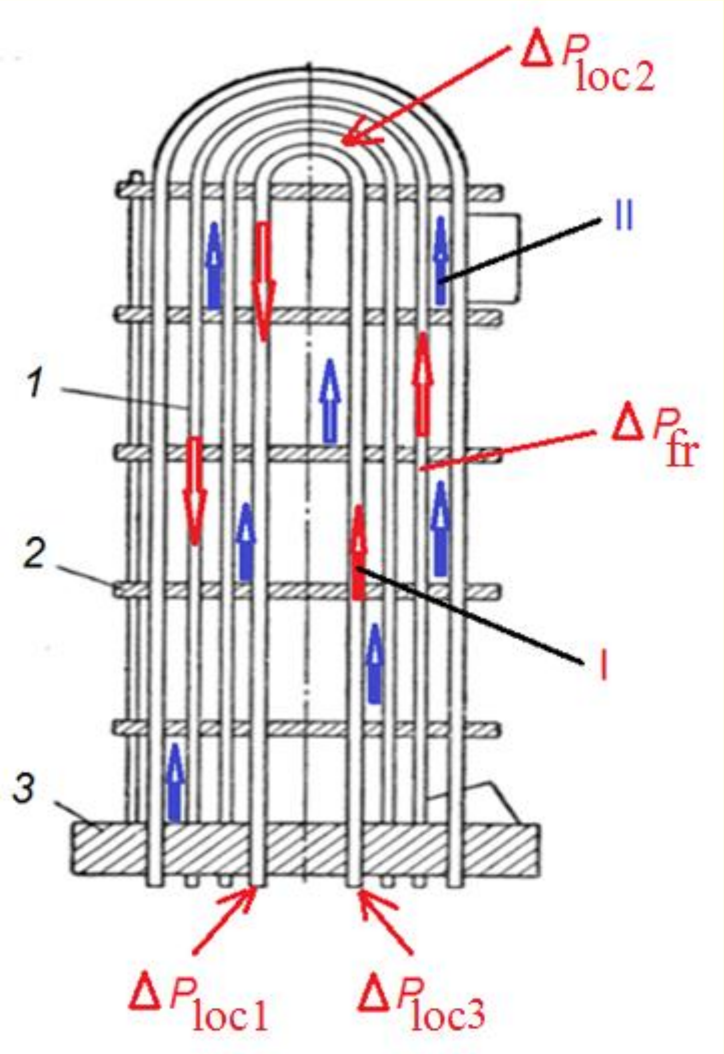


Fig. Calculation scheme

1 – heat exchange tubes;

2 – tube supports;

3 – tube sheet;

I – coolant channel(tubes);

II – working fluid annulus/channel (intertubular space)

General equation

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

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

Coolant channel – heat-exchange tubes

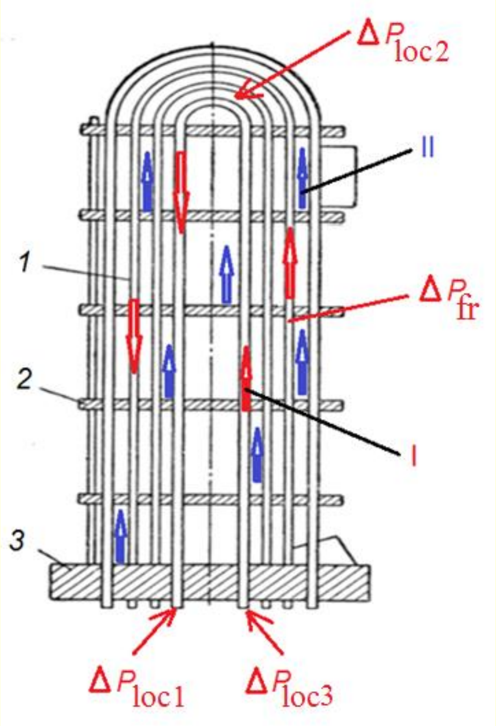
$$\boxed{\Delta p_h = \Delta p_{fr} + \Delta p_{loc1} + \Delta p_{loc2} + \Delta p_{loc3}}$$

frictional pressure drop

inlet pressure drop

pressure drop due to 180° turn

outlet pressure drop



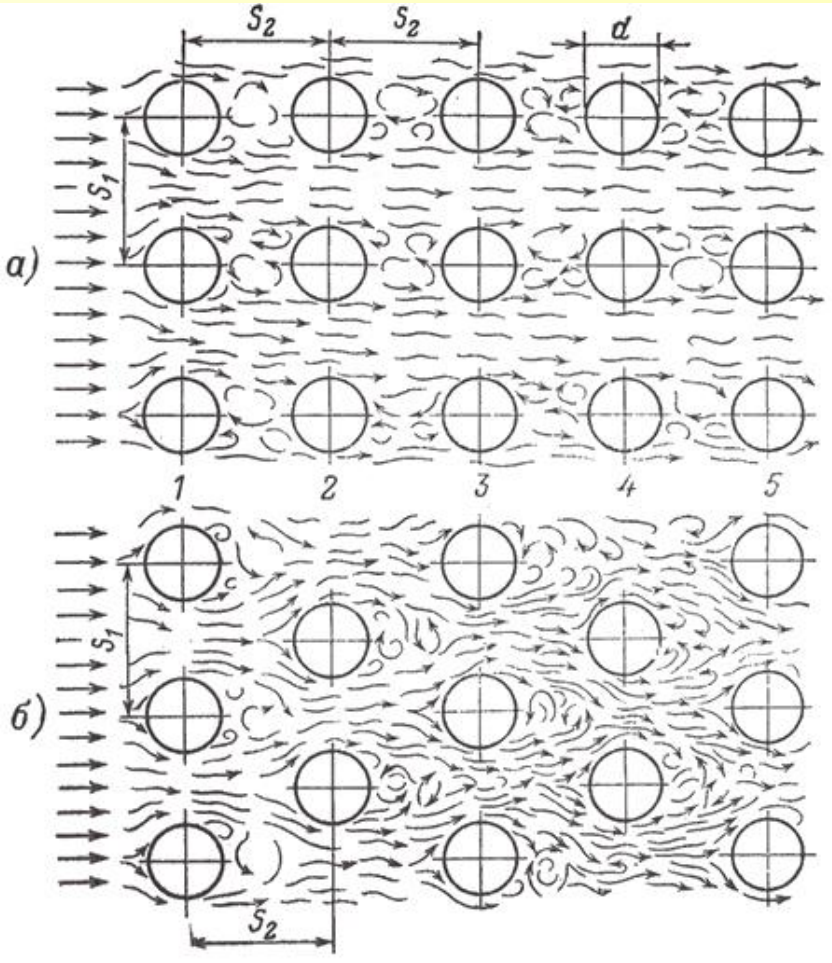
ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

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

General equation

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

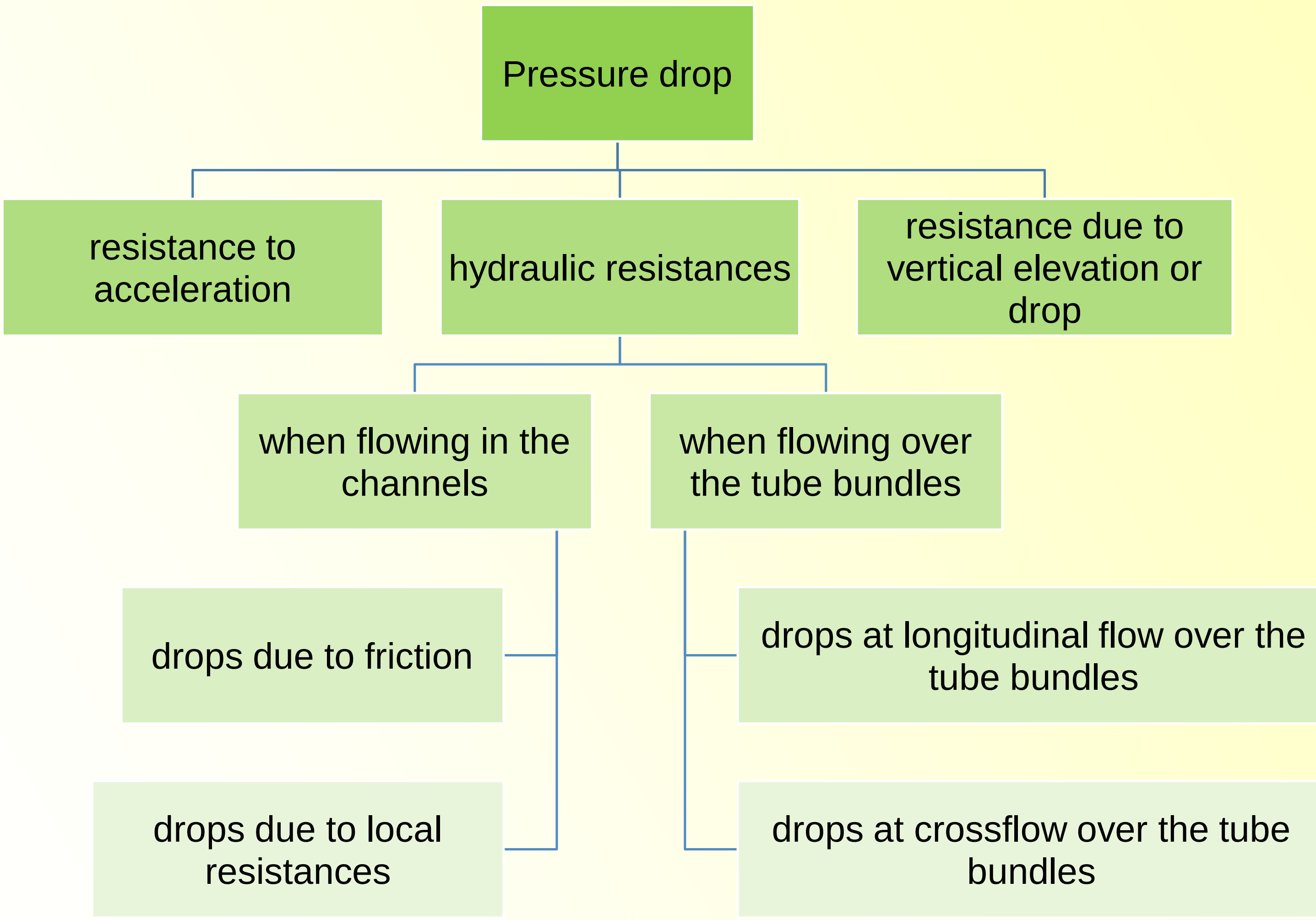
Note. Pressure drops due to friction and local resistance are calculated together



Calculation of pressure drop constituents in single-phase flow

ТОМСКИЙ
ПОЛИТЕХНИЧЕСКИЙ
УНИВЕРСИТЕТ

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



For correct hydraulic calculation it is necessary to determine…

1. Flow regime (turbulent or laminar)
2. Representative parameters (temperature, dimension and velocity.

Determination of flow regime

To determine the flow regime used Reynolds number

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

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 turbulent flow regime in the circular pipes is set is usually taken to be 2300-2800.

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

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

Question. Why turbulent flow is most often used in energy heat exchangers?

The main advantage of the turbulent regime is the high intensity of heat transfer.

Representative dimension

d_{in} – inner diameter *(for flow in circular tubes);*

d_h – hydraulic diameter *(for flow in non-circular channels and longitudinal flow over the bundles);*

d_{out} – outer diameter *(for crossflow over the bundles);*

l_{tube} – tubes length *(for natural convection and vertical arrangement of tube bundles)*

Hydraulic diameter

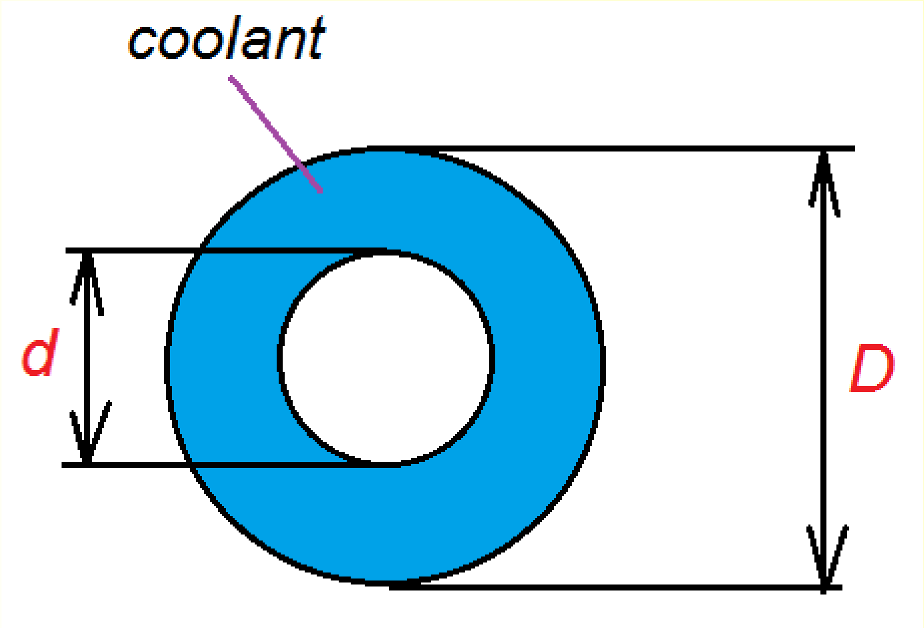
General equation for hydraulic diameter

$$d_h = \frac{4 \cdot F}{P_w}$$

Here F – flow area of the channel;

P_w – wetted perimeter

Question. What is the hydraulic diameter for the case of movement of the coolant in the



General equation for hydraulic diameter

$$d_h = \frac{4 \cdot F}{P_w}$$

ТОМСКИЙ
ПОЛИТЕХНИЧЕСКИЙ
УНИВЕРСИТЕТ

Hydraulic diameter

Hydraulic diameter for infinite bundle array (not accounting for the vessel perimeter):

- for triangular array

$$d_h = d_{out} \cdot \left(2 \cdot \sqrt{3} \cdot x^2 / \pi - 1\right) = d_{out} \cdot \left(1{,}103 \cdot x^2 - 1\right)$$

- for square array

$$d_h = d_{out} \cdot \left(4 \cdot x^2 / \pi - 1\right) = d_{out} \cdot \left(1{,}273 \cdot x^2 - 1\right)$$

Here $x = S/d_{out}$ - relative pitch (spacing)

Hydraulic diameter

Hydraulic diameter for tube banks with other tube arrangement (annular, in-line, staggered arrays)

$$d_h = d_{out} \cdot \left(4 \cdot x_{avr}^2 / \pi - 1\right) = d_{out} \cdot \left(1{,}273 \cdot x_{avr}^2 - 1\right)$$

Here $x_{avr} = \sqrt{x_1 \cdot x_2}$ - average pitch (spacing)

Representative dimension

Representative dimension for crossflow over the bundles is – outer diameter d_{out}

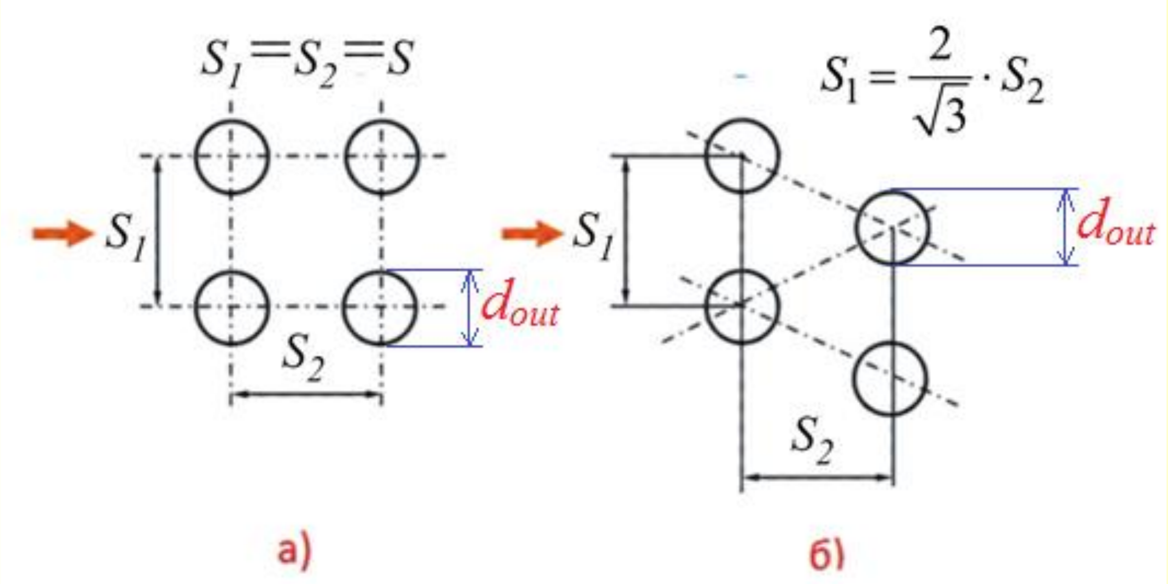


Fig. Tube arrangement in a bank
a – square array; b – triangular array

Representative temperature

- cross-section averaged fluid temperature;
- mean temperature of a boundary layer;
- wall surface temperature

Representative velocity

- w_{avr} - cross-section averaged velocity (movement of fluid flow in tubes or channels);
- w_{avr} - fluid velocity in the intertubular space during longitudinal movement between the tubes;
- w_{nar} - fluid velocity in the narrow cross-section of a bundle (for cross flow in a bundle of tubes)

Representative velocity

Cross-section averaged velocity (movement of fluid flow in tubes or channels)

$$w_{avr} = \frac{G}{f_{ch} \cdot \rho_{avr}}$$

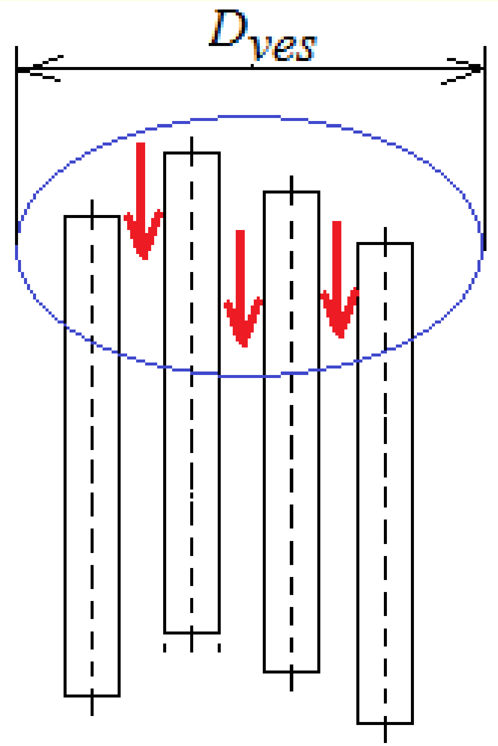
$$f_{ch} = \frac{\pi \cdot d_{in}^2}{4} \cdot n_{tube}$$

Here f_{ch} – flow area of the channel; n_{tube} – number of tubes in a bundle; G – mass flow rate of a medium; ρ_{avr} – coolant's mean density

ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Representative velocity

Fluid velocity in the intertubular space by longitudinal movement between the tubes



$$w_{avr} = \frac{G}{f_{its} \cdot \rho_{avr}}$$

$$f_{its} = \frac{\pi}{4} \cdot \left(D_{ves}^2 - n_{tube} \cdot d_{out}^2 \right)$$

Here f_{its} – flow area of the intertubular space;

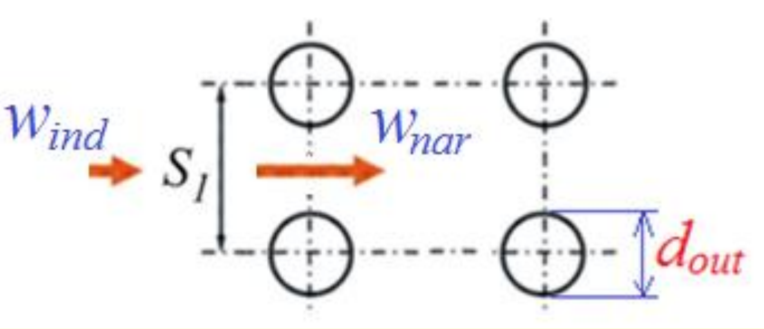
D_{ves} – vessel diameter

ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Representative velocity

Fluid velocity in the narrow cross-section of a tube bundle (for cross flow in a bundle of tubes)

$$w_{nar} = \frac{w_{ind}}{\eta_{cc}}$$



Here w_{ind} – indraft velocity (input velosity);

η_{cc} – contraction coefficient

$$\eta_{cc} = \frac{d_{out}}{S_1}$$

ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Selection of optimum velocity

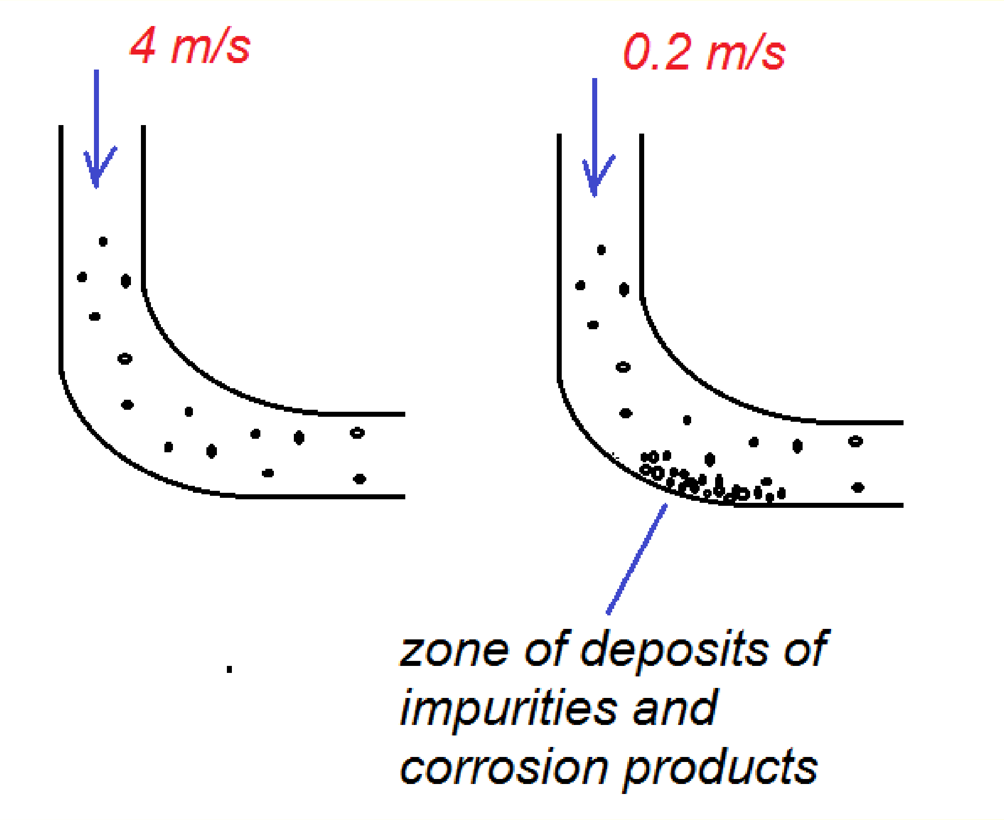
Factors that restrict the max velocity:

- 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 (stagnant) zones and accumulation of impurities there;
- natural circulation disruption

About danger of dead (stagnant) zones and accumulation of impurities there;



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

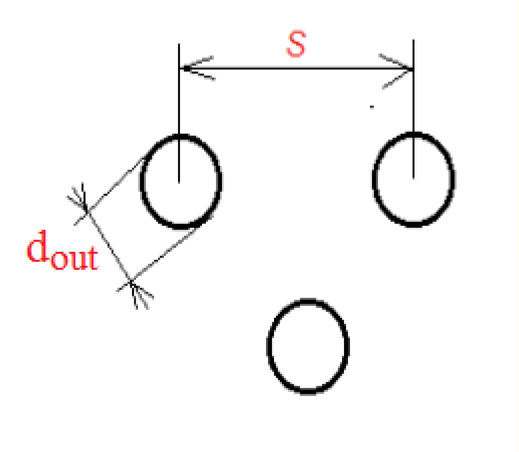
Notes. Data on equivalent roughness Δ:

- ✓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)

ТОМСКИЙ ПОЛИТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ

Friction factors

Bundles of circular rods



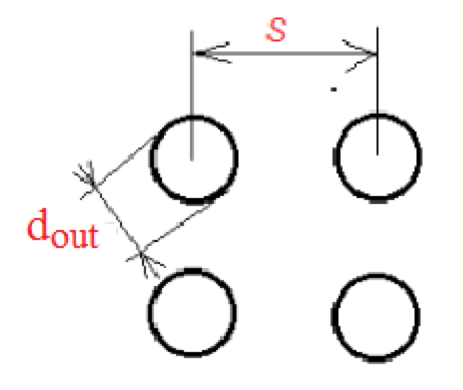
triangular arrangement

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

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

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

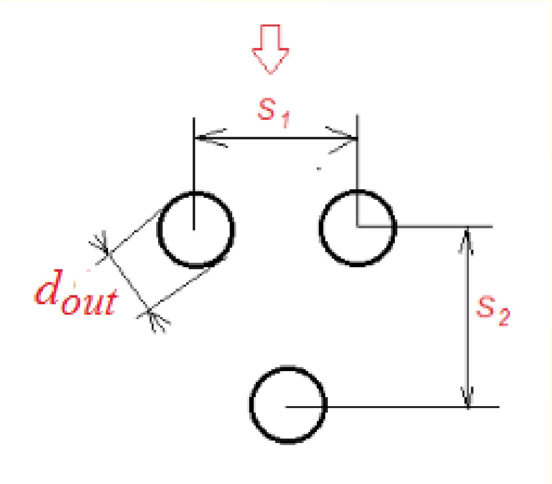
General equation

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

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

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

Pressure drop (cross flow over tube bundles)

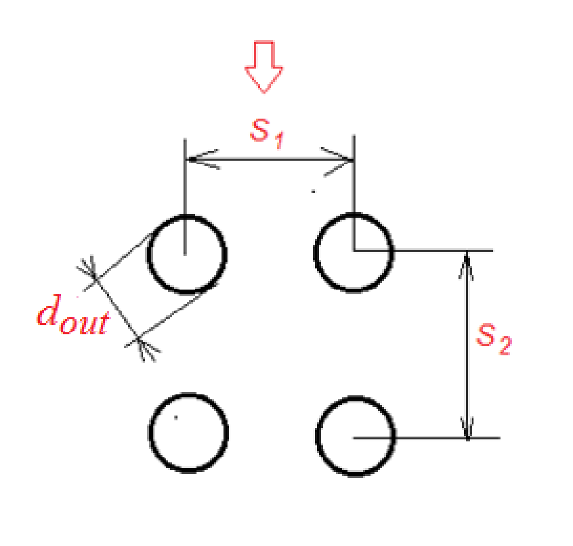


For staggered bundles

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

Here Z_2 – number of rows along the flow direction

Pressure drop (cross flow over tube bundles)



For corridor tube bundles

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

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;

w_1 , w_2 – velocity of the medium in the beginning and at the end of the passage

Example

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

P_{st}=13 MPa; t_{st}=500 ^oC; 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	VVER-440	VVER-1000
η, %	50…70	60…77
Pump type	Main circulation pump 317 (GTSN-317)	Main circulation pump 195 (GTSN-195)

Thank you for attention