NPP STEAM GENERATORS

Heat transfer in NPP SGs.

General issues.

Overview

1. Peculiarities of heat transfer in NPP SGs.
2. Temperature patterns of heat transfer surface.
3. Heat transfer characteristic parameters.

Peculiarities of heat transfer in NPP SGs

Heat transfer processes determine the efficiency and reliability of steam generators in many respects.

Convective heat transfer for the coolant and for the working fluid is characteristic of all elements of the steam generator.

Convective heat transfer intensity is specified by:

- geometry of heat transfer surface;
- coolants' physical parameters;
- flow hydrodynamics.

Peculiarities of heat transfer in NPP SGs

Coolant in NPP steam generators are almost always single phase. The equations for calculating heat transfer in this case are quite simple.

The working fluid in some parts of the NPP steam generators is in a two-phase state. The equations for calculating heat transfer in two-phase flows are very complex or have low accuracy.

Temperature patterns of heat transfer surface

SG's reliability in continuous long-term operation requires the execution of the condition

$$t_w < (t_m)^{perm}$$

t_w – wall temperature;
$(t_m)^{perm}$ - max permissible temperature of the tube wall material

Temperatures $(t_m)^{perm}$ for various steel grades

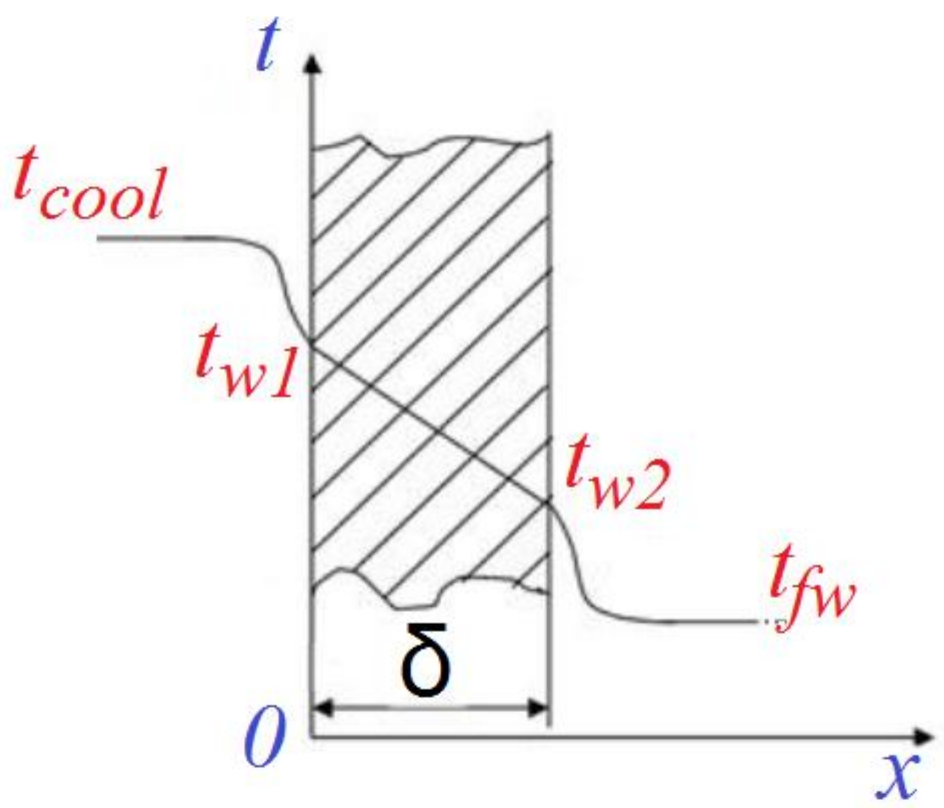
Steel 10, steel 20	t≤425 °C
12MX	t ≤ 510 °C
12X1MФ	t ≤ 540 °C
1X18H10T	t ≤ 600 °C

Temperature patterns of heat transfer surface

Brief characteristics of steels applied for NPP SGs:

- steel 10 – constructional, carbon, high-grade;
- steel 20 – constructional, carbon, high-grade;
- steel 12MX - heat resistant, low-alloy;
- steel 12X1MФ - heat resistant, low-alloy;
- steel 1X18H10T - corrosion-resistant, heat-resistant

Question. What determines the temperature difference $\Delta = t_{cool} - t_{fw}$ in a flat wall?



Temperature patterns of heat transfer surface

Temperature drop values depend on:

- heat flux q;
- heat transfer coefficient k

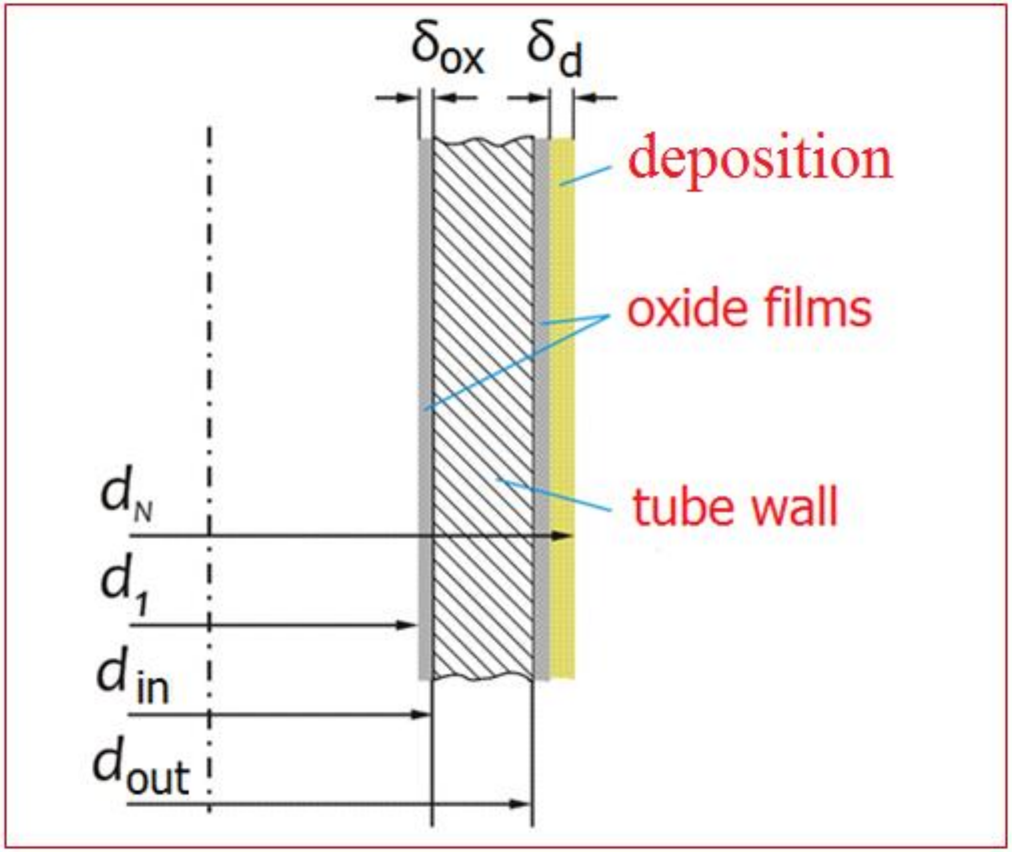
$$\boxed{\Delta t = q \cdot k}$$

For NPP SGs the typical ratio is

$$\boxed{q_{SH} \leq q_{E} \leq q_{Ev}}$$

Here q – heat flux; k – heat transfer coefficient

Intensity of heat transfer in NPP SGs



In operating conditions heat exchange tubes act like multi-layered walls that include:

- pure metal of the tubes;
- oxide films;
- deposition (on the working fluid side)

Heat transfer coefficient of multi-layered cylindrical wall per inner surface unit

$$k = \left[d_1 \cdot \left(\frac{1}{\alpha_{in} \cdot d_1} + \frac{1}{2 \cdot \lambda_{wall}} \cdot \ln \frac{d_{out}}{d_{in}} + \sum \frac{1}{2 \cdot \lambda_i} \cdot \frac{d_i}{d_{i-1}} + \frac{1}{\alpha_{out} \cdot d_N} \right) \right]^{-1}$$

Here d_{out}, d_{in} - outer and inner tube diameters;
d_i, d_{i-1} - outer and inner diameters of the i-layer;
α_{out}, α_{in} – heat transfer coefficients of the outer and inner side of the wall;
λ_w, λ_i – thermal conductivity of the wall and i-layer materials

Note. This equation for heat transfer coefficient is typically used if

$$\alpha_{in} << \alpha_{out}$$

Heat transfer coefficient of multi-layered plain wall

$$k = \left(\frac{1}{\alpha_{in}} + \frac{\delta_{wall}}{\lambda_{wall}} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_{out}} \right)^{-1}$$

Here δ_{wall}, δ_i - thickness of the tube wall and i-layer (oxide films, deposits)

Note. This equation for heat transfer coefficient is used if

$d_{out} / d_{in} < 2$

Characteristic heat resistance values, m²·°C/W

$$\boxed{1/\alpha_2 = (2,5 \div 3)\cdot 10^{-5}}$$

$$\boxed{\begin{aligned} \delta_{wall}/\lambda_{wall} &= (2...20)\cdot 10^{-5} \\ \delta_{fd}/\lambda_{fd} &= \partial o\, 20\cdot 10^{-5} \\ \delta_{ox}/\lambda_{ox} &= (2...20)\cdot 10^{-5} \end{aligned}}$$

Conclution. *All values of resistens are about the same.*

Example of depositions on NPP SG tubes (one of the nuclear power plants in Ukraine)

tube

depositions

Criterion equations are usually used to calculate heat transfer

$$Nu = \frac{\alpha \cdot d}{\lambda}$$

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

$$\mathrm{Pr} = \frac{\nu}{a} = \frac{\mu \cdot c_P}{\lambda}$$

$$Pe = \mathrm{Re} \cdot \mathrm{Pr} = \frac{w \cdot d}{a}$$

In these formulas:

ν – kinematic viscosity coefficient, m^2/s;

μ – dynamic viscosity coefficient, Pa/s;

c_P – specific heat capacity, J/(kg·K);

a – thermal diffusivity, m^2/s;

d – representative dimension, m;

w – representative velocity, m/s

Criterion equations are usually used to calculate heat transfer

$$Gr = \frac{g \cdot \beta \cdot l^3 \cdot \Delta t}{\nu^2}$$

in this formula:

Δt – wall-fluid temperature drop, K;

g – gravitational acceleration, m/s^2;

l – length, m;

β –volumetric thermal expansion coefficient, 1/K

Nusselt number is the main criterion in heat transfer calculations

- is a dimensionless heat transfer coefficient

$$Nu = \frac{\alpha \cdot d}{\lambda}$$

Reynolds number

- determines the fluid's hydrodynamic pattern

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

Prandtl number

- characterizes the fluid's physical properties

$$\mathbf{Pr} = \frac{\nu}{a} = \frac{\mu \cdot c_P}{\lambda}$$

Peclet number

➢ represents the ratio of molecular heat transport to convective heat transport in a flux

$$Pe = \mathrm{Re} \cdot \mathrm{Pr} = \frac{w \cdot d}{a}$$

Grashof number

- Grashof's criterion characterizes the ratio of viscous friction and lift. This criterion describes the regime of free fluid movement.

$$Gr = \frac{g \cdot \beta \cdot l^3 \cdot \Delta t}{\nu^2}$$

Determining values in heat transfer calculations

1. Representative dimension.
2. Representative temperature.
3. Representative velocity.

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)*

Representative dimension

General equation for hydraulic diameter

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

Here F – flow area of the channel;

P_w – wetted perimeter

Representative dimension

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)

Representative dimension

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

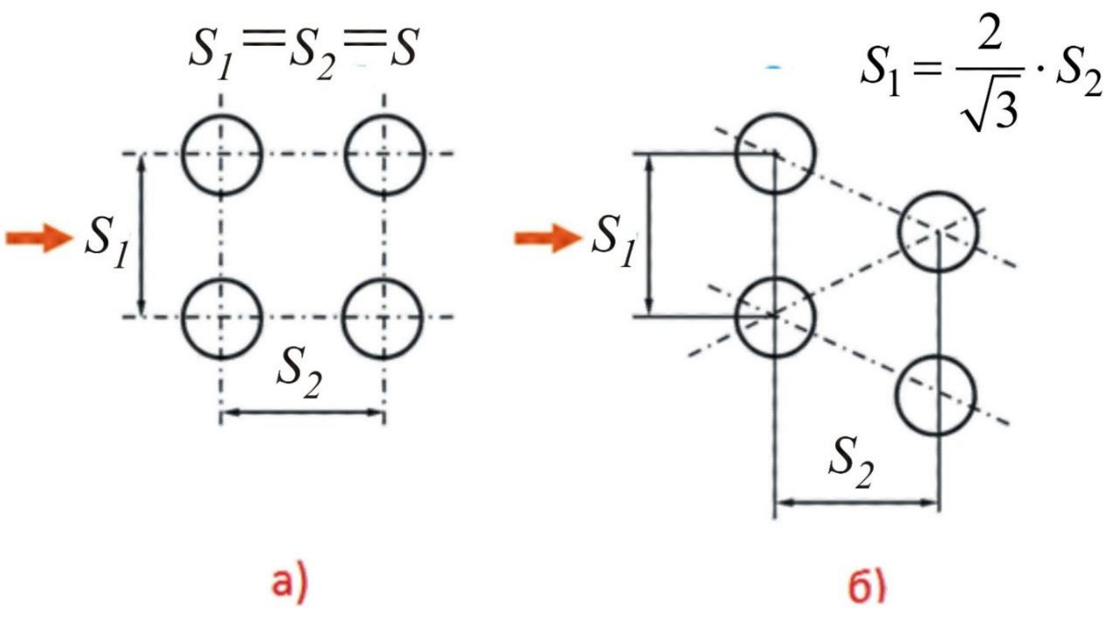


Fig. Tube arrangement in a bank
a – square array; b – triangular array

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} - velocity of the fluid flow in intertubular space (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

Representative velocity

Fluid velocity in the intertubular space (between the tubes)

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

Here f_{its} – flow area of the intertubular (annular) space; D_{ves} – vessel diameter

Indicate the correct formula for f_{its}

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

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

Representative velocity

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

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

$$f_{nar} = L \cdot \left(B - n_{cros} \cdot d_{out} \right)$$

Here f_{nar} – flow area of the narrow cross-section of a bundle;

L, B – length and width of a bundle;

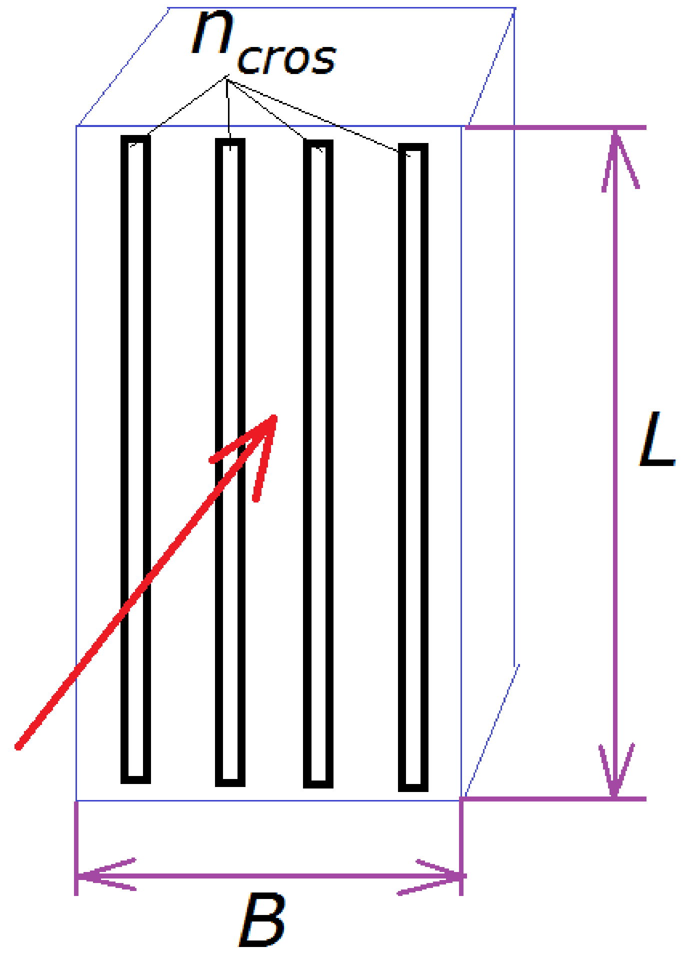
n_{cros} – number of tubes in the cross section of the tube bundle

Representative velocity

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

Flow area of the narrow cross-section of a bundle

$$f_{nar} = L \cdot \left(B - n_{cros} \cdot d_{out}\right)$$



Representative velocity

2. 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

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

Thank you for attention