NPP Steam Generators

Boiling heat transfer

Outline

1. Classification of boiling modes.
2. Determination of boundaries of zones with characteristic heat transfer conditions.
3. Recommendations for heat transfer coefficient calculation

Boiling process occurs only in the 2nd circuit of NPP SGs

Boiling economizers and evaporators

The SG design and parameters determine the hydrodynamic conditions and structure of two-phase flows:

- in evaporators of *once-through* SGs boiling occurs under the conditions of forced flow with high velocities;
- in evaporators with *natural circulation* boiling occurs under the conditions of natural flow with low velocities

Boiling processes can be classified by

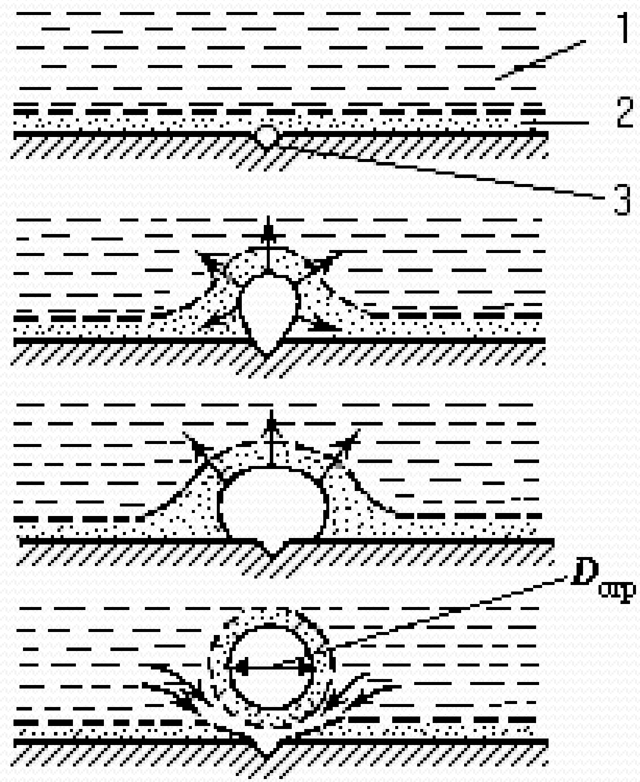
- *location* (in tubes, in intertubular space)
- *flow pattern* (forced circulation, natural circulation);
- *flow regime* (bubbly, film etc.)

Mechanism of steam bubble formation on the surface

The formation of steam bubble requires some *overheating of fluid* above its saturation temperature, which depends on fluid purity and presence of nucleation points.

Near the surface, from which heat is driven off to fluid, fluid superheating is max; surface irregularities serve as nucleation points of bubbles.

Mechanism of steam bubble formation on the surface



Reasons for heat transfer intensity growth upon boiling

- heavy *turbulization* of boundary layer due to growth and departure of steam bubbles;
- *heat transfer from surface* into a steam bubble when a microscopic fluid layer evaporates at the bubble root;
- *transfer* of latent *evaporation heat* inside a bubble

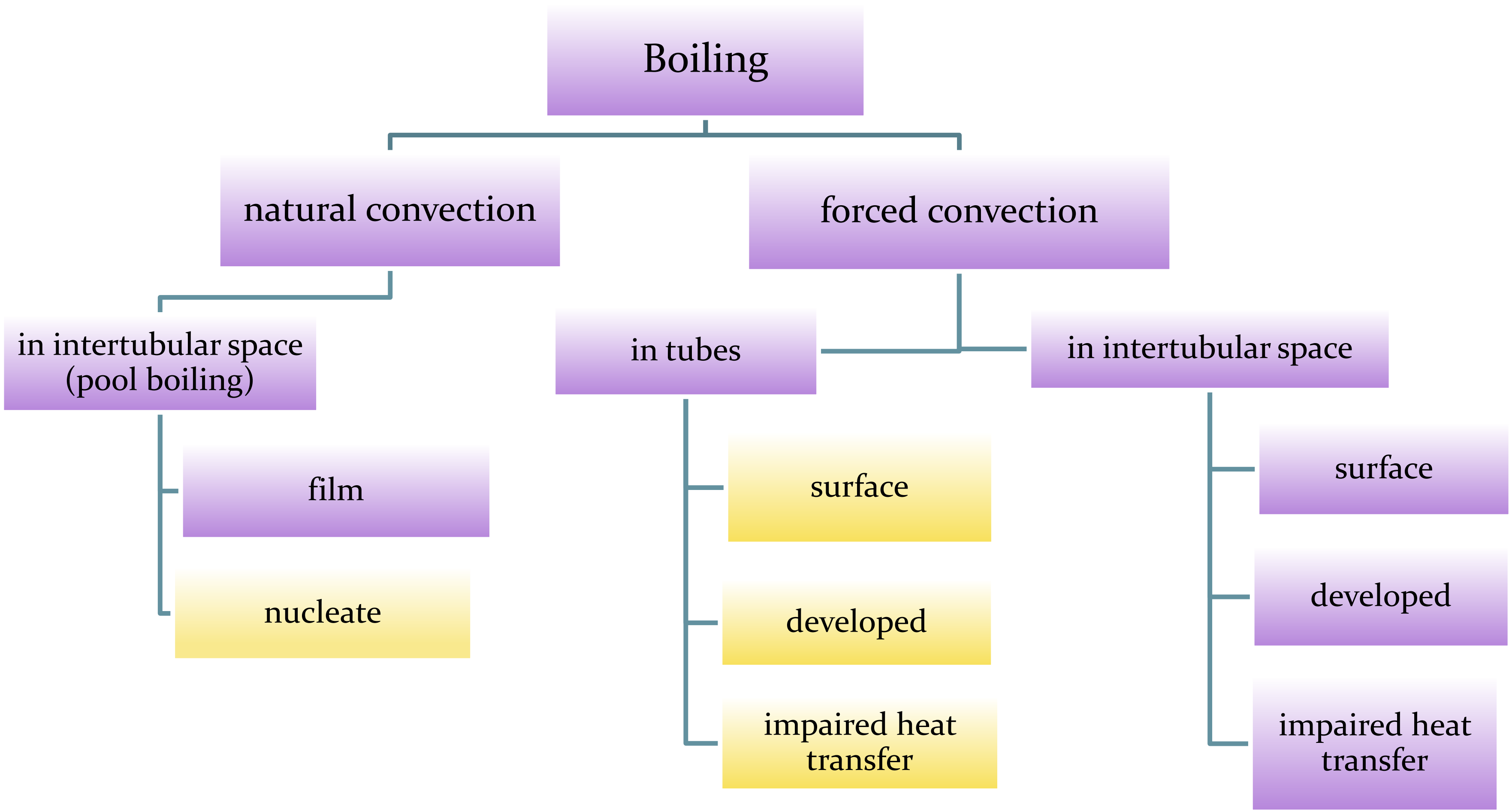
Boiling mode- **nucleate**

- can occur at *different flow structures* (bubbly, dispersed-annular, etc.);
- is characterized by *high heat transfer coefficient* and constant wall temperature

Boiling mode- **film**

- occurs when a *continuous steam film* is formed on heat exchange surface;
- is characterized by sharp *increase in wall temperature*

Formula selection algorithm for heat transfer coefficient calculation (two-phase flow)



Boiling at natural convection in intertubular space (pool boiling)

Heat transfer coefficient calculation for boiling in a large volume (pool boiling)

TsKTI formula

$$\alpha_{pb} = 4,34 \cdot q^{0,7} \cdot \left(p^{0,14} + 1,35 \cdot 10^{-2} \cdot p^{2} \right)$$

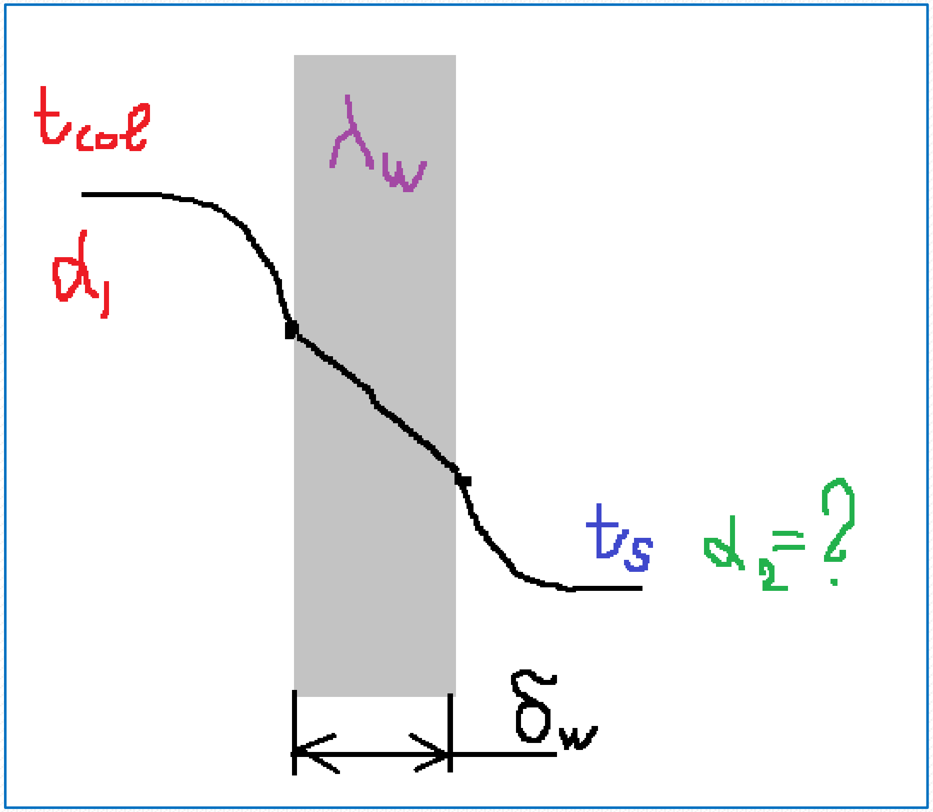
$$\alpha_{pb} = \frac{10,45}{3,3 + 0,0113 \cdot \left(t_S - 100 \right)} \cdot q^{0,7}$$

Kuzmin formula

$$\alpha_{pb} = 3,195 \cdot p^{0,75} \cdot q^{0,67}$$

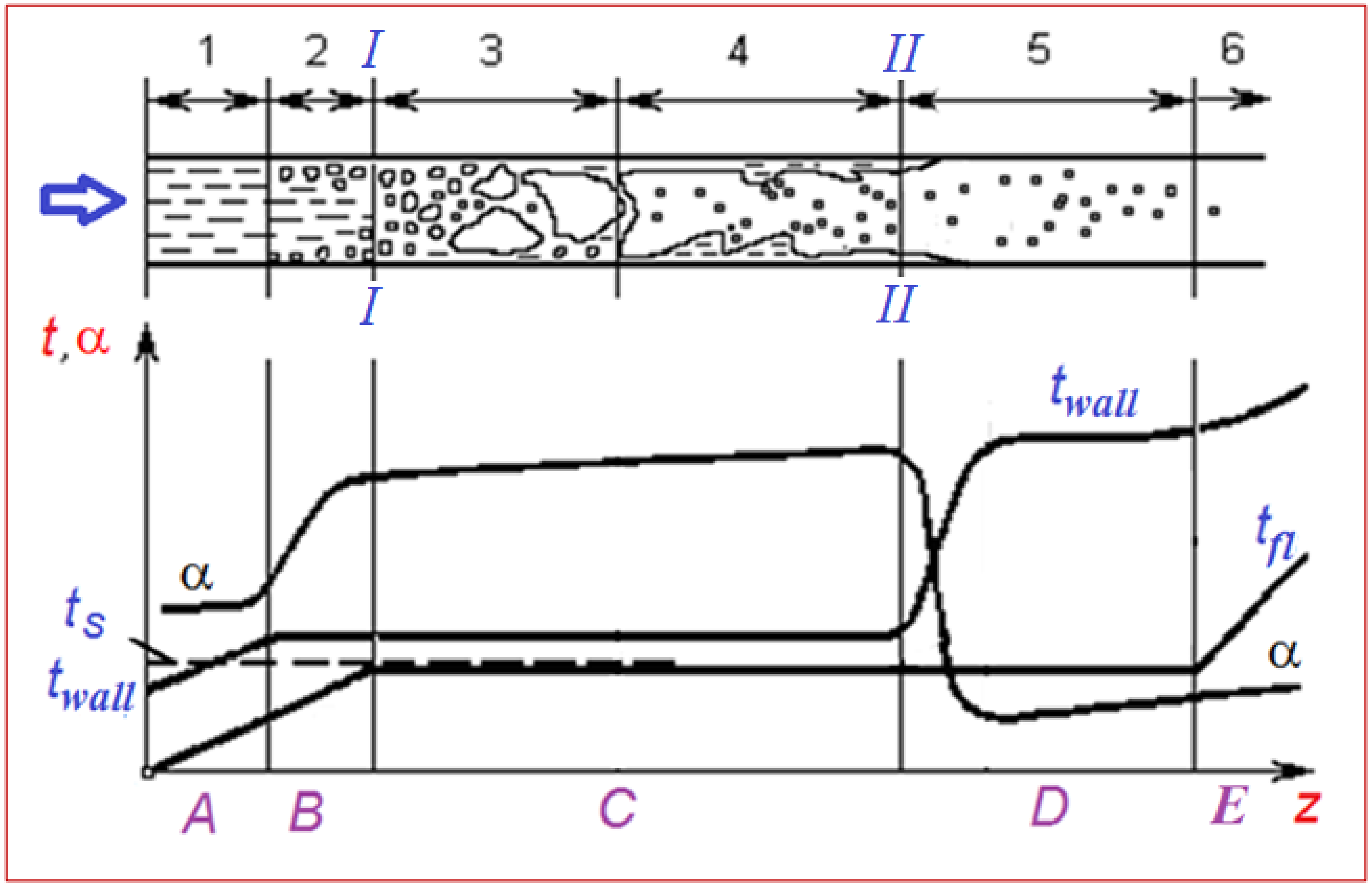
Here: α_{pb} – W/(m²· ºC)
p – pressure, MPa; *q* – heat flux, W/m²;
t_S – saturation temperature at pressure *p, ºC;*

Method for calculating heat transfer during boiling in a large volume

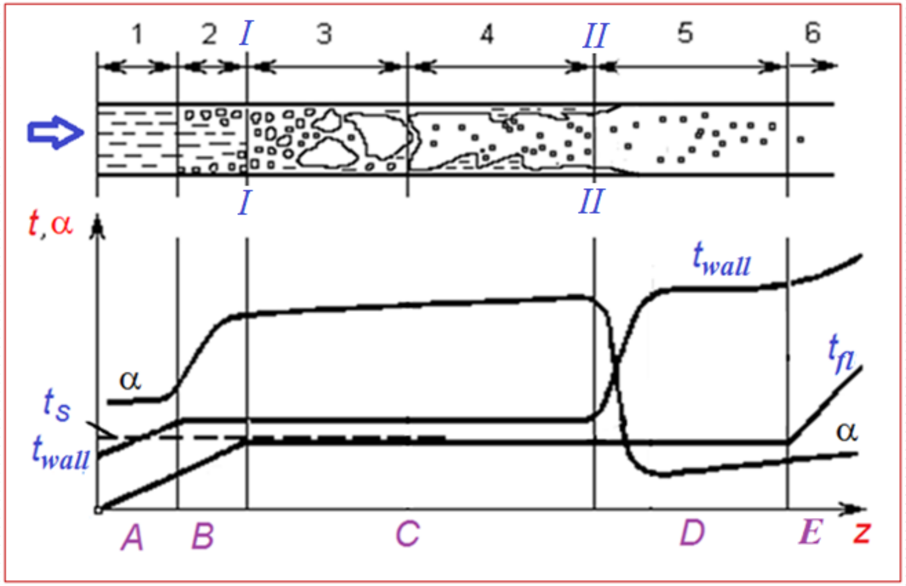


Boiling at forced flow in channels

Two-phase flow regimes and characteristic heat transfer regions



Two-phase flow regimes and characteristic heat transfer regions



Here α – heat transfer coefficient, W/(m^{2}·°C);

t_S – saturation temperature, °C;

t_{wall} – wall temperature, °C;

t_w – water temperature, °C

Characteristic flow regimes

1- water (single-phase flow);
2…5 – two-phase flows:
  2 –bubbly;
  3 – slug-bubbly;
  4 – dispersed-annular;
  5 – dispersed;
6 – superheated steam (single-phase flow)

Characteristic heat transfer regions

A (1) – convective heat transfer (non-boiling water);
B (2) – surface boiling zone;
C (3, 4) – developed boiling zone;
D (5) – impaired heat transfer zone;
E (6) – convective heat transfer (superheated steam)

Determination of zone boundaries with characteristic heat transfer conditions

- beginning of *surface* boiling region, cross-section ***I-I***;
- beginning of *impaired* heat transfer region, cross-section ***II-II***

Beginning of surface boiling region

When a tube wall reaches a temperature that exceeds saturation temperature by a definite value Δt_{sbs} , bubbles are formed on the surface (boiling process).

This overheating Δt_{sbs} depends on:

- flux parameters (velocity, temperature, pressure);
- material and condition of surface (roughness);
- presence of dissolved or suspended impurities

Note: «sbs» means surface boiling starts

Beginning of surface boiling region

Expression to identify the beginning of surface boiling region

$$\Delta h_{sbs} = h' - h_{sbs} = 0,3 \cdot q^{1,1} \cdot d_h^{0,2} \cdot (\rho w)^{-0,9} \cdot (\rho''/\rho')^{0,3}$$

Here h_{sbs} – water enthalpy in the beginning of surface boiling region, kJ/kg;
h' - saturated water enthalpy, kJ/kg;
q – heat flux, W/m²;
d – tube diameter, m;
ρ', ρ'' - saturated water and saturated steam density;
ρw – mass velocity, kg/(m²·s).

Beginning of heat transfer impairment region

In the heat transfer impairment region the steam-water mixture flow has a dispersed structure – fluid droplets are distributed over steam.

Certain portion of droplets evaporates in the flux nucleus, while heat is driven off from the wall by means of steam convection.

Heat transfer is significantly impaired, the heating surface temperature increases sharply (heat transfer crisis of the 2^{nd} type).

Beginning of heat transfer impairment region

$$x_{bsq} = 1 - 0,86 \cdot \exp\left[-\frac{19}{(\rho w) \cdot \sqrt{d_h / (\rho' \cdot \sigma)}} \right]$$

Here x_{bsq} – mass steam quality in the beginning of the heat transfer impairment region (boundary mass steam quality);
d_h – hydraulic diameter of the channel, m;
ρ' - density of saturated water;
ρw – mass velocity, kg/(m²·s);
σ – surface tension, N/m

Peculiarities of heat transfer calculation for forced boiling water flow in tubes

- along with thermal load it is necessary to take account of the effect of flow velocity on boiling process;
- in case of high steam quality it is necessary to take account of increasing velocity of the flow due to its changing structure;
- in the impaired heat transfer region (in post critical zone), heat and mass exchange on the heated surface of the channel must be also considered

Heat transfer coefficient in surface boiling region

$$\alpha/\alpha_{pb} = \left\{ 1 + \left[\alpha_{pb} \cdot \left(\frac{1}{\alpha_{conv}} - \frac{t_s - t_w}{q} \right) \right]^{-3/2} \right\}^{2/3}$$

Here α_{conv} – heat transfer coefficient in convective region, W/(m²· °C);

α_{pb} – heat transfer coefficient calculated by formulas for pool boiling, W/(m²· °C);

q – heat flux, W/m²;

t_s – saturation temperature, °C;

t_w – mass average water temperature, °C

Heat transfer coefficient in the developed boiling region

Jensen's formula

$$\alpha = \sqrt{\alpha_{conv}^2 + \left(0,7 \cdot \alpha_{pb}\right)^2}$$

Here α_{conv} – heat transfer coefficient in convective region, W/(m²· °C);
α_{pb} – heat transfer coefficient calculated by formulas for pool boiling, W/(m²· °C)

Heat transfer coefficient in impaired heat transfer region

Miropolsky's formula

$$Nu = 0,023 \cdot \left\{ \mathrm{Re}'' \cdot \mathrm{Pr}_{wall} \cdot \left[x + \frac{\rho''}{\rho'} \cdot (1-x) \right] \right\}^{0,8} \cdot Y;$$

$$Y = 1 - 0,1 \cdot \left(\frac{\rho'}{\rho''} - 1 \right)^{0,4} \cdot (1-x)^{0,4};$$

$$Nu'' = \frac{\alpha \cdot d_h}{\lambda''}; \quad \mathrm{Re}'' = \frac{\rho\omega \cdot d_h}{\mu''};$$

$$x = \frac{x_{bsq} + 1}{2}$$

Heat transfer coefficient in impaired heat transfer region

Nomenclature for Miropolsky's formula:

x_{bsq} – mass steam quality in the beginning of impaired heat transfer region;
q – heat flux, W/m²;
d_h – hydraulic diameter of the tube, m;
ρ', ρ'' - density of saturated water and steam;
λ'' - thermal conductivity factor of saturated steam, W/(m· °C);
μ'' - dynamic viscosity coefficient of saturated steam, Pa·s;
Pr'' - Prandtl number for steam at wall temperature;
ρw – mass velocity, kg/(m²·s)

Thank you for attention