NPP steam generators

Two-phase flows and their characteristics

Lecture plan

- Classification of two-phase flows
- Characteristics of two-phase flows
- Calculation of pressure drops for two-phase flow

DEFINITION OF 'TWO-PHASE FLOW'

Mixture of fluid and steam coexisting in a flow in different forms (bubbles, droplets, etc)

One phase is saturated water, the other phase is dry saturated steam

Classification of two-phase flows

- by character of the mutual phase flow (upstream co-current flow, downstream co-current flow, counter-current);
- by flow pattern (bubbly, slug, dispersed-annular, dispersed);
- by character of phases' relative disposition (homogeneous model, heterogeneous model);
- by intensity of interaction (equilibrium, quasi-equilibrium, non-equilibrium);
- by time character of the processes (stationary, non-stationary)

Types of two-phase flows depending on flow structure

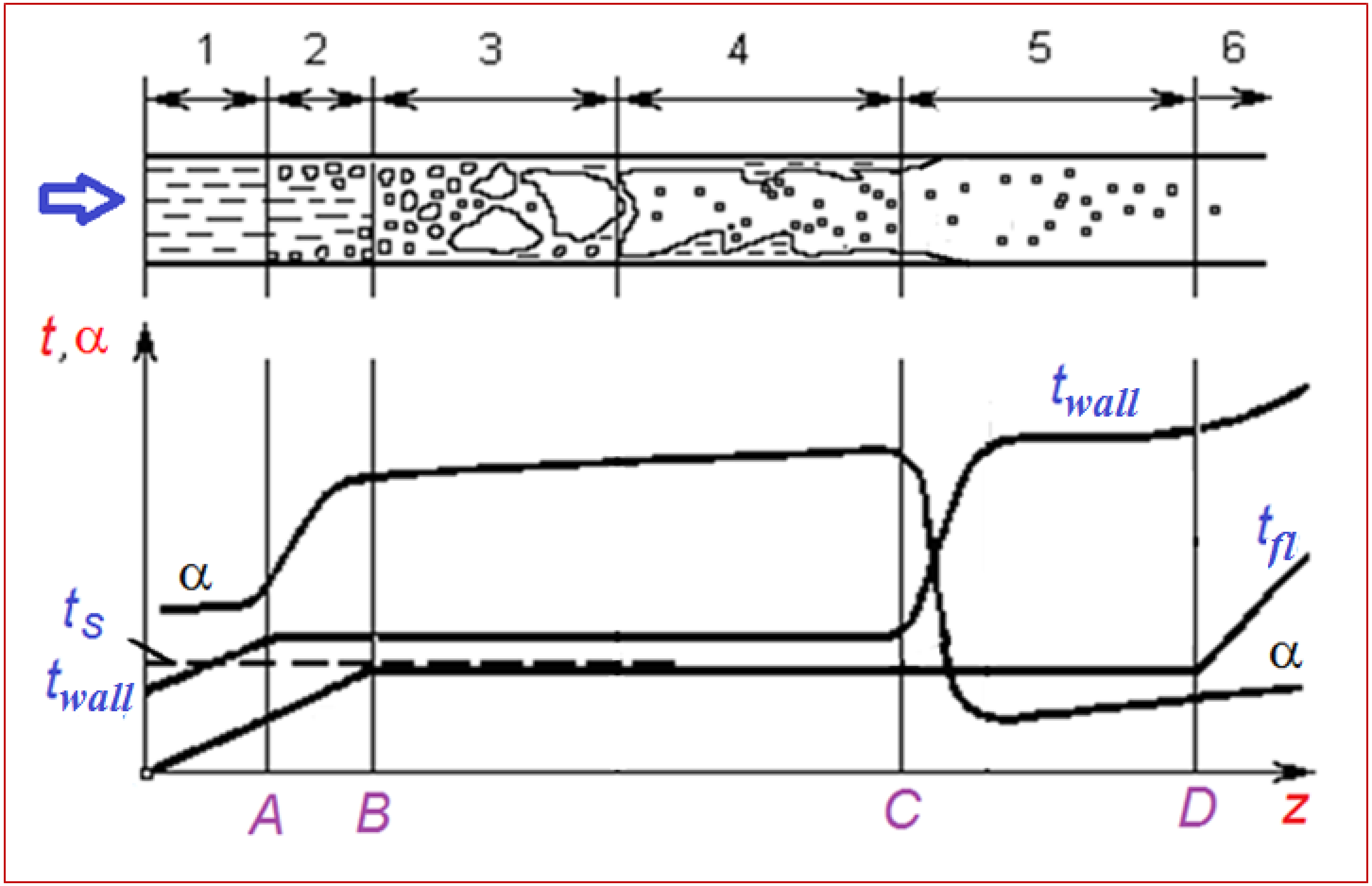
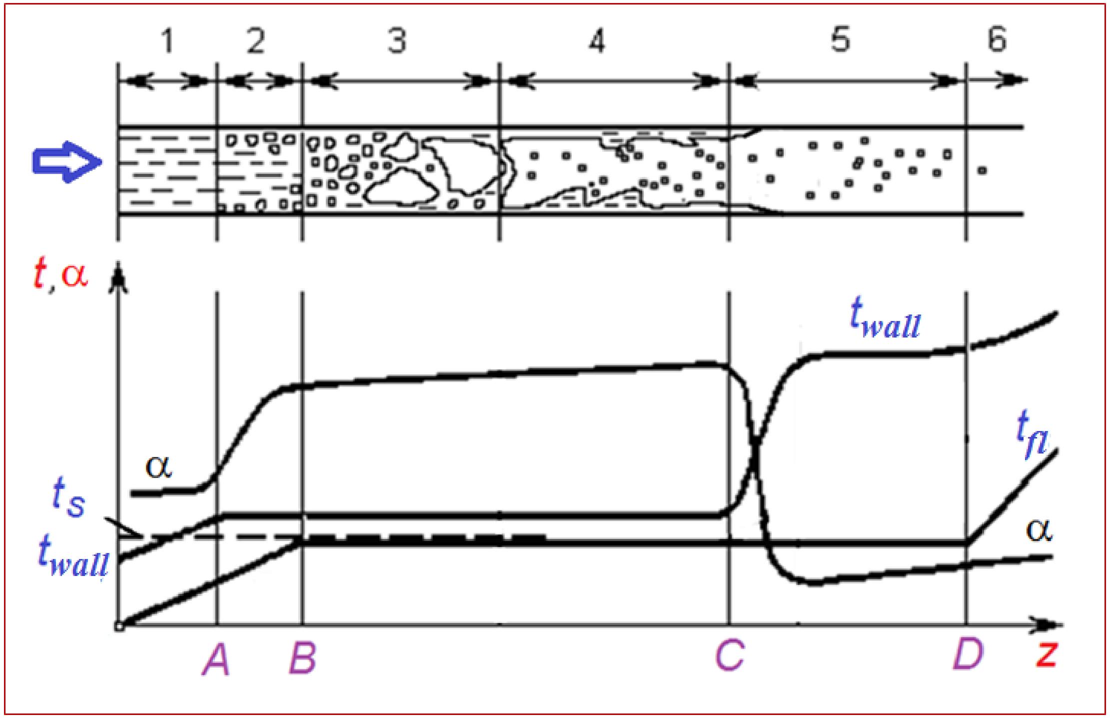


Fig. Change in flow structure along the length of the heated channel

TYPES OF TWO-PHASE FLOWS DEPENDING ON FLOW STRUCTURE



Legend:

t_S – saturated temperature;

t_{wall} – wall temperature (heating surface);

t_{fl} – bulk temperature of the medium (flow);

α – heat transfer coefficient from the wall to the two-phase flow

Characteristics of flow patterns

1- water (single-phase flow);
2 – bubbly (mist) flow (Small bubbles are evenly distributed in water flow.);
3 – slug flow (The flow comprises small bubbles and large ‘slugs’.);
4 – dispersed annular flow (Water film is flowing along the channel wall, steam with water droplets – in the centre of the channel.);
5 – dispersed flow (All the water in the form of droplets is distributed in the steam flow.);
6 – superheated steam (single-phase flow)

Two-phase flow characteristics

1. Flow rates
2. Steam quality
3. Velocities
4. Void fractions
5. Integral characteristics of the mixture

1. Flow rates

1.1. Flow rates

$$D_{mix} \text{ or } D = D_{st} + D_w$$

Here:

D_{mix} or D – *mass flow rate of the mixture*

D_{st} – *mass flow rate of steam*

D_w – *mass flow rate of water*

1. Flow rates

1.2. Volumetric flow rates

$$V_w = D_w \cdot \upsilon'$$

$$V_{st} = D_{st} \cdot \upsilon''$$

Here: υ', υ'' - specific volumes of water and steam

2. Steam quality

$$x = \frac{D_{st}}{D}$$

$$x = \frac{h - h'}{h'' - h'} = \frac{h - h'}{r}$$

Here: h – enthalpy of the mixture;
h', h'' - enthalpy of saturated water and steam

2. STEAM QUALITY

Heat balance for any section of the evaporation zone

$$D \cdot h = D_{st} \cdot h'' + \left(D - D_{st}\right) \cdot h'$$

$$\frac{D}{D} \cdot h = \frac{D_{st}}{D} \cdot h'' + \frac{D - D_{st}}{D} \cdot h'$$

$$h = x \cdot h'' + \left(1 - x\right) \cdot h'$$

$$\boxed{x = \frac{h - h'}{h'' - h'}}$$

3. Velocities

3.1. Circulation rate

$$w_0 = \frac{D \cdot \upsilon'}{f_{ch}} = \frac{D}{f_{ch} \cdot \rho'}$$

3.2. Mass velocity

$$\rho' \cdot w_0 = \rho_1 \cdot w_1 = \rho_{mix} \cdot w_{mix} = \ldots = \rho w = \frac{D}{f_{ch}} = const$$

Here: ρ_{mix}, w_{mix} – density and velocity of the mixture;
f_{ch} – area of the channel's flow passage

3. Velocities

3.3. Superficial flow velocities of the phases

$$\omega_0' = \frac{D_w \cdot \upsilon'}{f_{ch}}$$

$$\omega_0'' = \frac{D_{st} \cdot \upsilon''}{f_{ch}}$$

Here: υ', υ'' - specific volumes of water and steam

Expression of Circulation rate w_0 through superficial velocities of phases

$$D = D_{st} + D_w = \ldots$$

$$D = f_{ch} \cdot \frac{w_0}{\upsilon'} \qquad D_{st} = f_{ch} \cdot \frac{w_0''}{\upsilon''} \qquad D_w = f_{ch} \cdot \frac{w_0'}{\upsilon'}$$

$$w_0 = w_0' + \frac{\upsilon'}{\upsilon''} \cdot w_0''$$

3.4. ACTUAL PHASE VELOCITIES

$$w' \text{ or } w_w = \frac{D_w \cdot \upsilon'}{f_w} = \frac{w_0' \cdot f_{ch}}{f_w}$$

$$w'' \text{ or } w_{st} = \frac{D_{st} \cdot \upsilon''}{f_{st}} = \frac{w_0'' \cdot f_{ch}}{f_{st}}$$

Here: f_w, f_{st} – areas occupied by water and steam in cross-section of the channel

4. Slip coefficient

$$R = \frac{w_{st}}{w_w}$$

If the lifting motion of two-phase flow, then

$$R > 1 \quad or \quad R < 1$$

If the two-phase flow is lowering then

$$R > 1 \quad or \quad R < 1$$

Formula for slip coefficient calculation

$$R = 1 + 2,54 \cdot d_h^{0,25} \cdot \frac{(1-\pi)}{\upsilon' \cdot (\rho w)}$$

$$R = \left[1 + \left(0,6 + 1,5 \cdot \beta^2\right) \cdot (1-\pi) \cdot Fr^{-0,25}\right]$$

Here:

$$\pi = \frac{p}{p_{cr}};$$

$$Fr = \frac{w_0^2}{g \cdot d_h};$$

$$p_{cr} = 221,3 \cdot 10^5 \ Pa$$

5. Void fractions

$$\varphi = \frac{f_{st}}{f_{ch}} = \frac{f_{st}}{f_{st} + f_w} = \frac{1}{1 + \frac{f_w}{f_{st}}}$$

Actual volumetric void fraction

$$w_w = \frac{D_w \cdot \upsilon'}{f_w}$$

$$w_{st} = \frac{D_{st} \cdot \upsilon''}{f_{st}}$$

$$\varphi = \frac{1}{1 + \frac{f_w}{f_{st}}} = \ldots = \frac{x}{x + R \cdot \frac{\upsilon'}{\upsilon''} \cdot (1 - x)} = \frac{1}{1 + R \cdot \frac{\upsilon'}{\upsilon''} \cdot \frac{1 - x}{x}}$$

5. Void fractions

$$\beta = \frac{V_{st}}{V_{st} + V_w}$$

volumetric void fraction

$$V_w = D_w \cdot \upsilon'$$

$$V_{st} = D_{st} \cdot \upsilon''$$

$$\beta = \frac{x}{x + \frac{\upsilon'}{\upsilon''} \cdot (1 - x)} = \frac{1}{1 + \frac{\upsilon'}{\upsilon''} \cdot \frac{1 - x}{x}}$$

5. Integral characteristics of mixture

5.1. Mixture density

actual

$$\rho_{mix} = \varphi \cdot \rho'' + (1 - \varphi) \cdot \rho'$$

$$\rho_{mix} = \rho' - \varphi \cdot (\rho' - \rho'')$$

height-averaged

$$\overline{\rho}_{mix} = \rho' - \overline{\varphi} \cdot (\rho' - \rho'')$$

5. Integral characteristics of mixture

5.2. Mixture velocity

$$\omega_{mix} = \omega_0 \cdot \frac{\rho'}{\rho_{mix}}$$

$$\omega_{mix} = \frac{\omega_0}{1 - \varphi \cdot \left(1 - \frac{\rho''}{\rho'}\right)}$$

Calculation of actual volumetric steam quality φ

Volumetric void fraction is determined by the equation

$$\beta = \left[1 + \frac{\rho''}{\rho'} \cdot \frac{(1-x)}{x} \right]^{-1}$$

Slip coefficients are calculated by

$$R = \left[1 + \left(0,6 + 1,5 \cdot \beta^2 \right) \cdot (1-\pi) \cdot Fr^{-0,25} \right]$$

Actual volumetric void fraction is given as

$$\varphi = \left[1 + R \cdot \frac{\rho''}{\rho'} \cdot \frac{(1-x)}{x} \right]^{-1}$$

Friction drop for flow in the channel

- Homogeneous flow model.
- Separated flow model (Lockhart-Martinelli method)

Calculation of friction pressure drop for homogeneous flow model

TSKTI method

For circular tubes

$$\Delta p_{fr} = \xi \cdot \frac{L}{d_h} \cdot \frac{(\rho w)^2}{2 \cdot \rho'} \cdot \left[1 + \psi \cdot \left(\frac{\rho'}{\rho''} - 1\right)\right]$$

Here $\psi = f(p, \rho w, x)$ is determined by means of nomographs;

ξ – friction factor of a single-phase flow for equal flow rate of fluid;

L, d_h – length and hydraulic diameter of the channel;

ρ', ρ'' - density of saturated water and steam

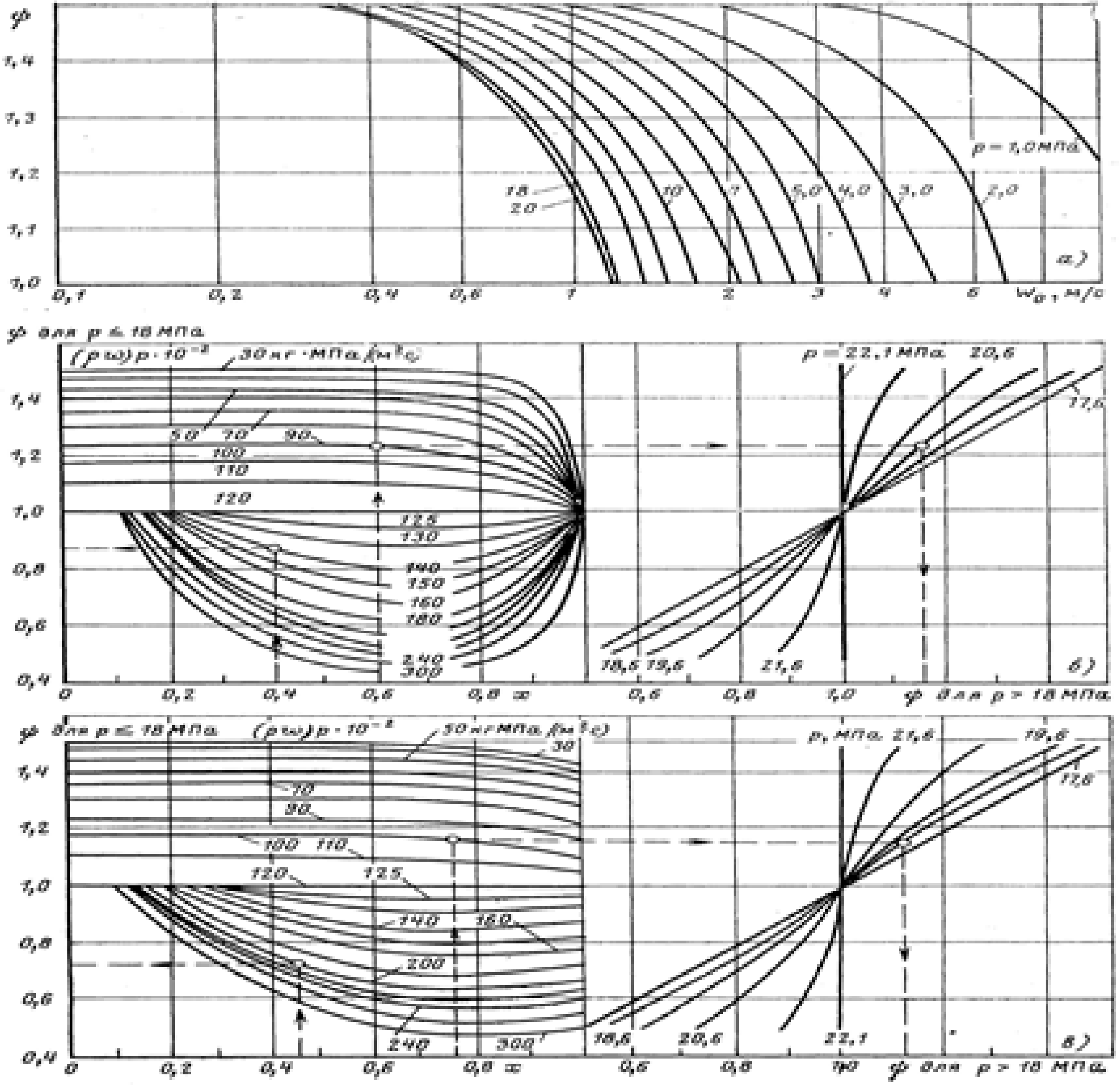


Рис. 2.5. Значения коэффициента ψ для $x < 0{,}7$ и $w_0 < 10$ м/с (а), для необогреваемых труб при $w_0 \geq 10$ м/с (б), обогреваемых труб при $w_0 \geq 10$ м/с (в)

Calculation of friction pressure drop for separated flow model

Lockhart-Martinelli method

$$\left(\frac{dp}{dz}\right) = \Phi_L^2 \cdot \left(\frac{dp}{dz}\right)_L \quad \textit{или} \quad \left(\frac{dp}{dz}\right) = \Phi_V^2 \cdot \left(\frac{dp}{dz}\right)_V$$

Here

$$-\left(\frac{dp}{dz}\right)_V = \frac{2 \cdot \xi'' \cdot x^2 \cdot (\rho\omega)^2}{d \cdot \rho''};$$

$$-\left(\frac{dp}{dz}\right)_L = \frac{2 \cdot \xi' \cdot (1-x)^2 \cdot (\rho\omega)^2}{d \cdot \rho'}$$

Calculation of friction pressure drop for separated flow model

Lockhart-Martinelli method

$$\mathrm{Re}_V = \frac{x \cdot d \cdot (\rho\omega)}{\mu''};$$

$$\mathrm{Re}_L = \frac{(1-x) \cdot d \cdot (\rho\omega)}{\mu'}$$

$$\xi = \frac{16}{\mathrm{Re}} \qquad npu\ \mathrm{Re} \le 2000;$$

$$\xi = 0{,}11 \cdot \left(\frac{\Delta}{d} + \frac{68}{\mathrm{Re}} \right)^{0{,}25} \qquad npu\ \mathrm{Re} > 2000$$

CALCULATION OF FRICTION PRESSURE DROP FOR SEPARATED FLOW MODEL

Lockhart-Martinelli method

$$X^2 = \frac{(dp/dz)_L}{(dp/dz)_V}$$

$$\Phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2};$$

$$\Phi_V^2 = 1 + C \cdot X + X^2$$

Regime (water-steam)	C
Turbulent-Turbulent	20
Laminar-Turbulent	12
Turbulent-Laminar	10
Laminar-Laminar	5

ORDER OF FRICTION PRESSURE DROP CALCULATION BY THE LOCKHART-MARTINELLI METHOD

1. Reynolds number for steam Re_V and water Re_L ;
2. Friction factor for steam ξ_V and water ξ_L;
3. Specific pressure drop for steam $(dp/dz)_V$ and water $(dp/dz)_L$;
4. Coefficient X^2;
5. Coefficient *C*;
6. Complex Φ^2 for steam and water;
5. Specific pressure drops for steam-water mixture (dp/dZ);
6. Total pressure drop due to friction for steam-water mixture

$$\Delta p_{fr} = \left(dp/dz\right) \cdot L$$

Here L – channel length

DROPS DUE TO LOCAL RESISTANCES IN TWO-PHASE FLOWS

$$\Delta p_{loc} = \Delta p_{loc.sph} \cdot \left[1 + x \cdot \left(\frac{\rho'}{\rho''} - 1 \right) \right]$$

Here $\Delta p_{loc.sph}$ - local resistance of a single-phase flow for equal flow rate of the medium of density *ρ';*

x – steam quality

DROPS DUE TO ACCELERATION IN TWO-PHASE FLOWS

$$\Delta p_{acc} = \rho'_{fin}\, w^2_{0\,fin} \left[1 + x_{fin} \left(\frac{\rho'_{fin}}{\rho''_{fin}} - 1 \right) \right] - \rho'_{in}\, w^2_{0in} \left[1 + x_{in} \left(\frac{\rho'_{in}}{\rho''_{in}} - 1 \right) \right]$$

Here x_{fin}, x_{in} – final and initial steam quality;

$w_{0,fin}$, $w_{0,in}$ – final and initial values of circulation rate;

ρ'_{fin}, ρ'_{in} – final and initial saturated water density;

ρ''_{fin}, ρ''_{in} – final and initial saturated steam density

STATIC PRESSURE DROP (DROP DUE TO VERTICAL HEAD VARIATION) IN TWO-PHASE FLOWS

Static pressure drop in the channel is defined as the sum of scales of the fluid columns for all of the channel sections.

Static pressure drop for flow in the j-section is given by the equation

$$\Delta p_{spd,j} = \left[\overline{\varphi}_j \cdot \rho'' + \left(1 - \overline{\varphi}_j\right) \cdot \rho' \right] \cdot h_j \cdot g$$

- $\overline{\varphi}_j$ – average actual volumetric void fraction in j-section
- ρ'' – saturated steam density
- ρ' – saturated water density
- h_j – height of the j-section

Static pressure drop (drop due to vertical head variation) in two-phase flows

Note. Static pressure drop is considered to be positive for upstream sections and negative for downstream sections.

Thank you for attention