# Lecture 3 «Heat emission during the boiling and condensation. Radiant heat exchange»

**Aim:** Describe heat emission during boiling and condensation. Characterize the radiant heat exchange.

**Lecture summary:** Boiling – an intensive process of evaporation occurring throughout the volume of the liquid when the pressure of a saturated vapor of the boiling liquid is equal to the external pressure. The boiling process is widely used in engineering (for example, in power engineering) and in chemical technology when evaporation of solutions in evaporators, separation of liquid mixtures by distillation and rectification, and evaporation of refrigerants.

An obligatory condition for the boiling of the liquid is the continuous supply of heat necessary for the vaporization process. Usually, heat is supplied from the heating surface in contact with the boiling liquid, and the temperature of the heating surface must exceed the temperature of the boiling liquid ($t_w > t_{boil}$).

The centers of formation of small bubbles (smallest hillocks on a hard surface, particles of pollution) are called *the centers of vaporization*. The intensity of the formation of bubbles increases to a certain extent with increasing temperature difference between the wall and the boiling liquid ($\Delta t = t_w - t_{boil}$). With increasing $\Delta t$, *the density of the heat flow q* increases, i.e. the amount of heat transferred by the fluid per unit time by a unit of the wall surface. The resulting mixing of the liquid, caused by the growth, detachment and bubbling of the bubbles, leads to an increase in the heat transfer coefficient $\alpha$ (Fig. 1).

This region in Fig. 1 corresponds to a *bubbling* or *nuclear* boiling regime, characterized by a relatively high rate of heat emission.
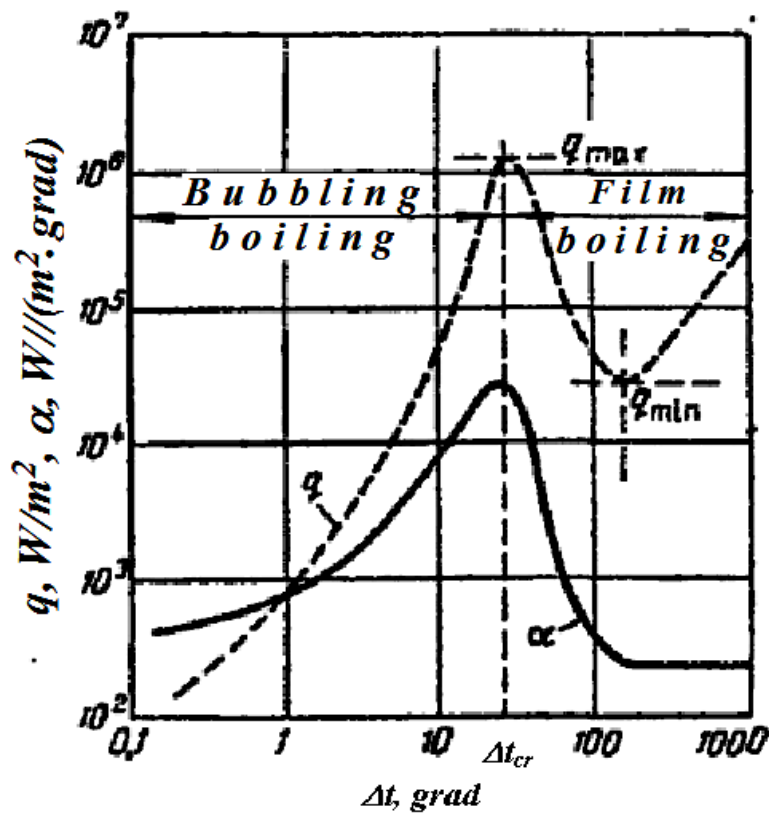


**Fig. 1.** Dependence of $\alpha$ and $q$ on $\Delta t$ for boiling water at p = 1 *atm*

With further increase of $\Delta t = \Delta t_{cr}$, the number of vaporization centers increases so much that the vapor bubbles are merged and the heating surface is covered by a poorly conductive heat film of superheated steam. Despite the fact that this film is not stable, its formation leads to a significant decrease in the value $\alpha$. The corresponding regime at which a transition occurs from bubbling regime of boiling to film regime is called the boiling crisis, and it is depicted by the right descending branch $\alpha = f(\Delta t)$ in Fig. 1 is called *film* boiling.

The value of the coefficient of heat transfer during the transition to the film boiling regime decreases by 20-40 times, which can lead to undesirable overheating of the heat exchange surface.

The film boiling regime is always undesirable, and in industry a boiling process in the region of a developed bubbling regime of high intensity should be organized, but without the danger of switching to a film mode.

The physical parameters of the liquid and vapor phases in the calculation formulas for heat transfer at boiling are taken at the boiling point (saturation), so it is often possible to represent these calculated ratios in a simple form, but with coefficients depending on the nature of the boiling liquid:

$$\alpha = AP^m q^n \tag{1}$$

For water and most other liquids $m \approx 0{,}4$ и $n \approx 0{,}7$; the values of the coefficient $A$ for various liquids are given in the reference literature.

In order for boiling not to pass from an intense bubbling to a film regime, it is necessary to estimate the critical values of the heat flow $q_{cr}$ and the difference $\Delta t_{cr}$. Experiments show that for many liquids $q_{cr}$ lies within the limits of 100–350 kW/m$^2$, and $\Delta t_{cr} \approx 20 - 25$ K. For water, $\Delta t_{cr} = 25$ K, $\alpha_{cr} \approx 45{\cdot}10^3$ W/(m$^2$·K) and $q_{cr} \approx 10^6$ W/m$^2$.

**Condensation of vapors.** In chemical equipment, heat emission from a condensing vapor is carried out, as a rule, under conditions of film condensation. In the case of film condensation, the thermal resistance is almost completely concentrated in the condensate film, the temperature of which on the wall side is assumed to be equal to the wall temperature $t_w$, and on the steam side - to the saturation temperature $t_{sat}$ of the vapor (Fig. 2). Compared with the thermal resistance of the film, the corresponding resistance of the vapor phase is negligible.

The film flow regime is a function of the Reynolds criterion: with increasing film thickness, the laminar flow of a film having a smooth surface goes into a wave, and then becomes turbulent. In addition to the physical properties of the condensate (density, viscosity, thermal conductivity), the heat transfer affects the wall roughness, its position in space, and the wall dimensions; in particular, with an increase in the surface roughness and height of the vertical wall, the condensate film thickens downward (Fig. 2).
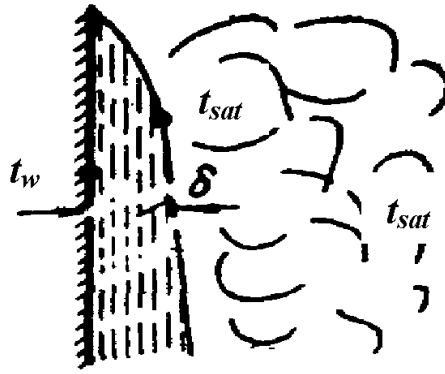
**Fig. 2.** Temperature distribution in film of condensate

The generalized equation for determining the heat emission coefficient from condensing vapors has the form

$$Nu = f(Ga, Pr, K) \tag{2}$$

This function, on the basis of processing experimental data, can be represented by the equation

$$Nu = C(Ga \cdot Pr \cdot K)^{0,25} \tag{3}$$

where $K = \dfrac{r}{c_l \Delta t}$ — the criterion characterizing the change in the aggregate state, or *the condensation criterion* ($r$ – the heat of condensation, $c_l$ – the heat capacity of the condensate, and $\Delta t = t_{sat} - t_w$).

The *Ga* and *Pr* criteria included in (3) are assigned to the condensate film. The expression for the condensation criterion $K$ is found by transforming the differential equation characterizing the boundary conditions. Criterion $K$ should be considered as a measure of the ratio of the heat flow expended on the phase transformation to the heat of overheating or supercooling of the phase at the temperature of its saturation.

When film condensation of a variable, laminating heat emission, is the thickness of the condensate film. The velocity of the vapor does not usually reach a value sufficient to disrupt the film, and does not enter into the uniqueness conditions. The generalized equation for film condensation instead of the *Re* and *Fr* criteria includes the $Ga = Re^2/Fr = gl/v^2$ derived criterion, which reflects the similarity of gravity forces acting on a heavier phase in a two-phase steam-condensate stream.

The coefficients of heat emission during the film condensation of water vapor vary within the range $(7\text{-}12) \cdot 10^3$ W/(m²·К). With drop condensation, they are much higher, but stable dropping condensation in industrial heat exchange equipment difficult to realize.

***Condensation of steam-gas mixtures.*** If even small impurities of air or other non-condensable gases are present in the vapor, the value $\alpha$ for the condensing vapor decreases sharply. Non-condensing gases gradually accumulate in the vapor space; at the same time, their partial pressure rises and, accordingly, the partial pressure of the vapor drops. In addition, the wall washing by the steam deteriorates and decreases $\Delta t = t_{sat} - t_w$.

The coefficient of heat emission in this case depends on the intensity of the interconnected processes of mass and heat exchange, which are determined by the composition of the vapor-

gas mixture, the nature of its flow, the physical properties of the components of the mixture, pressure, temperature, shape and size of condensation [1, 2].

## Thermal radiation

Thermal radiation – the result of intraatomic processes. The intensity of thermal radiation increases with increasing body temperature. Radiant energy spreads in the form of a stream of particles called quanta or photons, and has the properties of electromagnetic waves. Radiant heat exchange – the radiation of electromagnetic waves by one body and the absorption of radiation by another body.

Thermal and light radiation are of the same nature, only differ in wavelength. The wavelength of light rays are 0.4-0.8 μm, infrared rays are 0.8-400 μm. All bodies not only radiate, but also continuously absorb radiant energy. At the same temperature, the whole system of bodies is in mobile thermal equilibrium.

The amount of energy radiated by the body per unit of time throughout the wavelength interval (from $\lambda = 0$ to $\lambda = \infty$) by the unit of the surface $F$ of the body characterizes *the radiant emissivity E of the body*:

$$E = \frac{Q}{F\tau} \qquad (4)$$

where Q – the energy radiated by the body.

Of the total amount of energy $Q_o$ falling on the body, part of it is absorbed $Q_A$, some are reflected $Q_R$ and part passes through the bodies $Q_D$. Then the energy balance will be:

$$Q_A + Q_R + Q_D = Q_0 \qquad (5)$$

When dividing the equality by $Q_o$, we get:

$$Q_A/Q_0 + Q_R/Q_0 + Q_D/Q_0 = 1, \qquad (6)$$

where $\frac{Q_A}{Q_0} = A -$ characterizes the absorptive capacity of the body;

$\frac{Q_R}{Q_0} = R -$ characterizes the reflectivity of the body;

$\frac{Q_D}{Q_0} = D -$ characterizes the throughput of the body.

Consequently, the equality (6) can be represented as

$$A + R + D = 1 \qquad (7)$$

If the body absorbs all the energy incident on it, $A = 1$, and $R = D = 0$, such a body is called absolutely black. In nature, absolutely black bodies do not exist. The greatest absorption capacity is possessed by petroleum soot, for which $A = 0.9$-$0.96$.

If $R = 1$, then $A = D = 0$. This means that all energy falling on the body is reflected. Such a body is called absolutely white or mirror. For polished metals $R$ reaches 0.06-0.88.

If the body passes all the energy incident on it, such a body is called absolutely transparent or diathermic and $D = 1$, and $A = R = 0$. An example of such a body is pure air.

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The values $A$, $R$, $D$ depend on the physical properties of the body, the state of their surface, the temperature and the wavelength of the incident radiation.

*Kirchhoff found* that the ratio of the radiant power of any body to its absorptive capacity at the same temperature is a constant value equal to the emissivity of an absolutely black body:

$$\frac{E_1}{A_1} = \frac{E_2}{A_2} = \frac{E_0}{A_0} = f(t) \tag{8}$$

where $A_o$ – refers to an absolutely black body, $A_o = 1$.

The ratio of the emissivity of any body to the emissivity of absolutely black is called the degree of blackness:

$$\varepsilon = \frac{E}{E_0} \tag{9}$$

The degree of blackness $\varepsilon$ varies within 0-1 and depends on the nature of the body, the state of its surface and temperature.

*According to the law of Stefan-Boltzmann*, the emissivity of an absolutely black body $E_o$ is proportional to the fourth power of the absolute temperature of its surface

$$E_0 = K_0 T^4, \tag{10}$$

where $K_o = 5{,}7 \cdot 10^{-8}$ W/(m$^2 \cdot$K$^4$) – the constant of emission of an absolutely black body.

To simplify the calculations, the Stefan-Boltzmann equation is applied in the form:

$$E_0 = C_0 \left(\frac{T}{100}\right)^4, \tag{11}$$

where $C_o = K_o \cdot 10^8 = 5{,}7$ W/(m$^2 \cdot$K$^4$) – the emissivity of an absolutely black body.

**The radiation of gases** differs significantly from the radiation of solids. Gases radiate and absorb energy not in the entire wave band, as is typical for solids, but only in certain intervals of waves, in so-called bands, and outside these bands they are transparent. Gases radiate and absorb by all volume, and solid bodies - only by the surface.

**Questions to control:**
1. Describe the Describe heat emission during boiling and condensation.
2. Characterize the radiant heat exchange.

**Literature**
1. Lectures on the course «The main processes and devices of chemical technology»: textbook / Authors: Zh.T. Eshova, D.N. Akbayeva. – Almaty: Qazaq university, 2017. – 392 p. (in Russian)
2. Kasatkin A.G. Basic processes and devices of chemical technology. – M: Alliance, 2003. – 752 p.
3. Romankov P.G., Frolov V.F., Flisyuk O.M. Calculation methods of processes and devices in chemical technology (examples and tasks). – St.-Petersburg: Himizdat, 2009. – 544 p.