HEAT TRANSFER FROM A TRANSVERSE STEAMLINED CYLINDER DURING SURFACE BOILING IN A LIQUID FLUIDIZED BED

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During bubble boiling from a horizontal cylinder, the heat transfer is investigated located in a bed of solid particles fluidized with water and underheated to the saturation temperature. Numerical empirical relations are given.

The process of bubble boiling of liquids underheated to the saturation temperature is widely used for the efficient cooling of thermally stressed installations. In this paper the possibility is considered of intensifying the heat exchange during surface boiling by means of a fluidized bed of a solid dispersed material.

We have made an attempt to obtain experimental data about the effect of the fluidized particles of a solid on the intensity of the heat transfer during surface boiling and to correlate the data obtained. The analytic determination of the hydrodynamic characteristics during boiling, under fluidized conditions, and the corresponding heat-transfer coefficients is impossible, since the mechanism of the heat-transfer process has not been explained.

Apparently, the only paper associated with the subject of this present investigation is [1], in which the authors studied the process of the nonsteady cooling of a copper cylinder in a fluidized bed of copper spheres, undercooled by water. The boiling process in this case occurred in both the film and bubble regimes. The effectiveness of the fluidized bed was shown by the authors as a cooling medium, although numerical recommendations were not obtained.

An experiment to determine the heat transfer was conducted at atmospheric pressure on a facility made of stainless steel in a closed-circuit scheme. The hydrodynamically stabilized flow of water, fed by a pump from a discharge tank, fluidized the bed of dispersed material in a vertical channel of rectangular cross section with dimensions of 32×200 mm and a height of 800 mm. The distributing grid was a perforated plate with a diameter of the holes of 4.1 mm and a relative area of the holes of 29.3%.

The heat-releasing element was horizontally positioned, transverse to the flow, at a distance of 220 mm from the distributing grid; it was a section of a tube of 12Kh18N9T stainless steel, with an outside diameter of 5.44 mm, wall thickness of 0.27 mm, and a length of 200 mm. The surface roughness of the tube corresponded to class 5-6 according to All-Union State Standard (GOST) 2789-73. The tube was heated up by an alternating low-voltage electric current. In avoiding end effects the intensity of the heat release was determined by the voltage drop on the central section of the heater with a length of 100 mm. The current strength and the voltage drop were measured with Class-0.2 accuracy instruments. The average temperature of the tube surface was determined by the readings of a copper–Constantan thermocouple by the procedure of [2]. The water temperature at the inlet and outlet of the experimental channel was measured by two similar thermocouples. The emfs of all thermocouples were recorded by an F30K digital measurement assembly with a Class-0.05 accuracy. The saturation temperature was determined by the barometric pressure and the volume feed rate of the cooling medium by the pressure drop at the measurement diaphragm.

Alundum of three fractions with $d = 0.95$, 1.54, and 2.33 mm, density $\rho = 3590\ kg/m^3$, and porosity of the immobile filling $\varepsilon_0 = 0.46$ served as the material of the solid component particles.

The program of the present investigation included experiments to determine the intensity of the convective heat exchange both in the absence of boiling and with surface boiling of the cooling medium. The experimental data for the single-phase convective heat exchange of the water coincide with the dependence in [2].

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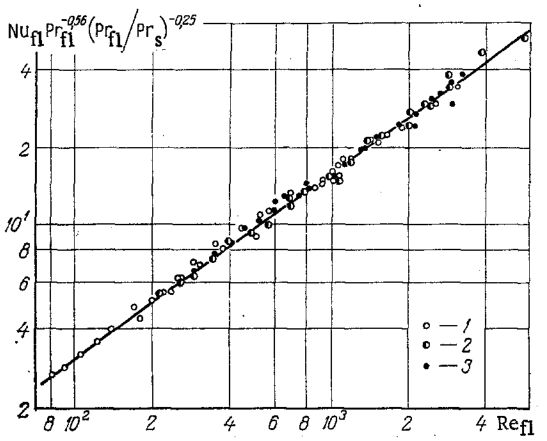

Fig. 1. Generalized experimental data for the convective heat exchange without boiling, according to Eq. (1): 1) d = 0.95; 2) 1.54; 3) 2.33 mm.

The experiments were conducted in sequences characterized by a constant velocity and mean-mass temperature of the water with a gradually increasing thermal loading in the steady-state thermal regime. The ranges of variation of the principal parameters were as follows: $q = 55$–2560 kW/m^2; $w = 0.06$–0.235 m/sec; $t_{fl} = 9$–$60°$C; $d = 0.95$–2.33 mm; $\varepsilon = 0.633$–0.914. The content of technological impurities in the water comprised residual carbonate hardness of 2.6–2.8 mg-eq/liter, alkalinity of 1.3–1.5 mg-eq/liter, chloride 15–20 mg-eq/liter, and oxygen 0.02–0.03 mg/liter. The data on the thermophysical properties of the coolant used for processing the experimental data were taken from the tables in [3].

In order to process the results on the intensity of the convective heat exchange without boiling, a procedure similar to that of [4] was used. For the characteristic velocity, the speed of filtration of the fluidizing medium in a narrow section divided by the average porosity of the fluidized bed was used. As the characteristic size, the equivalent diameter of the pore channel D was chosen, which was formed by particles of the solid component [5]. Figure 1 shows the experimental data for the intensity of convective heat exchange, which were processed by the least-squares method and led to the following similarity equation:

$$Nu_{fl} = 0.11\, Re_{fl}^{0.72} Pr_{fl}^{0.56} (Pr_{fl}/Pr_s)^{0.25}. \tag{1}$$

The mean-square deviation of the experimental points in Fig. 1 from the straight line, according to Eq. (1), amounts to 6.4%. Equation (1) was obtained in the following ranges of variation of the determining criteria: $Re_{fl} = 80$–5000, $Pr_{fl} = 3$–10, and $Pr_{fl}/Pr_s = 1.13$–1.70.

In [6] the authors used the average film temperature t_{fm}, determined by the expression $t_{fm} = (t_s + t_{fl})/2$, for processing the heat-exchange data with forced convection and for the characteristic temperature. In this paper, Eq. (1) can be represented in the form

$$Nu_{fm} = 0.109\, Re_{fm}^{0.72} Pr_{fm}^{0.63}, \tag{2}$$

and the determining criteria are found in the following ranges: $Re_{fm} = 100$–6000, $Pr_{fm} = 3.5$–8.

In order to correlate the experimental data for the heat transfer with the simultaneous existence of boiling and forced convection, the method proposed by Kutateladze [7] was used, which was modified by Pokhvalov and co-workers for the conditions of forced flow of underheated water in the tubes [8]. In [8] the relation

$$\frac{\vartheta}{\vartheta_0} = \left[1 + \left(\frac{\vartheta_0}{\Delta q}\alpha\right)^m\right]^{-1/m}, \tag{3}$$

was used for processing the experimental data, where

$$\vartheta = t_s - t_{sat} \tag{4}$$

$$\Delta q = q - \alpha(t_{sat} - t_{fl}). \tag{5}$$

For the conditions of the present experiment, α was calculated by Eq. (1). As a result of processing the experimental data, for the value of the wall superheating with a developed surface of boiling ϑ_0 the expression

$$\vartheta_0 = 4.44\, \Delta q^{0.14}. \tag{6}$$

was obtained. In this expression, the effect of superheating, the speed of filtration, and the particle size of the solid component on ϑ_0 is manifested through the value of Δq by relation (5). The experimental data for the temperature regime of the heater in the form of the dependence of the relative excess temperature of the wall

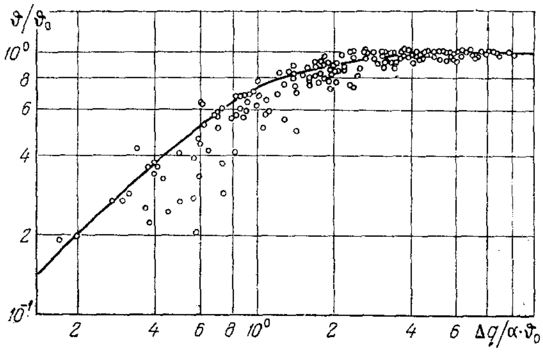

Fig. 2. Change of relative excess temperature of the heater wall for boiling with underheating. The curve corresponds to Eq. (3) for m = 2.

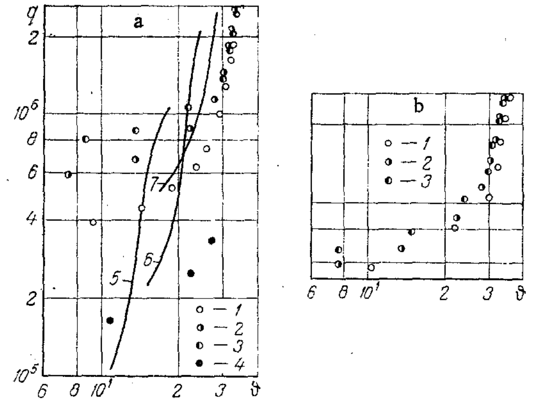

Fig. 3. Dependence of thermal flux density q (W/m^2) on the wall superheating ϑ (°K) with boiling in a fluidized bed of Alundum particles, ε = 0.784, p = 0.098 MPa for different values of underheating. a) d = 1.54 mm: 1) Δt = 39.3°K; w = 0.149 m/sec; 2) 59 and 0.148; 3) 78 and 0.144; 4) Δt = 31.5°K; w = 0.1213 m/sec; p = 0.294 MPa; δ = 11.43 mm [9]; 5, 6, 7) large volume, p = 0.201 MPa, δ = 1.6 mm, Δt equal, respectively, to 1.67; 39.4 and 82.3°K [10], and with different values of the speed of filtration and particle sizes of the solid component. b) Δt = 59°K; 1) d = 0.95 mm; w = 0.117 m/sec; 2) 1.54 and 0.148; 3) 2.33 and 0.185.

in the function on the value of the complex $\Delta q/\alpha\vartheta_0$ are shown in Fig. 2, in which the curve corresponding to Eq. (3) is also shown for m = 2.

Figure 3a shows the experimental points for the effect of underheating on the curves of surface boiling in a fluidized bed of Alundum particles with a diameter of 1.54 mm. It can be seen that with the exception of large values of wall superheating, where the effect of underheating is small, the thermal flux density for identical values of ϑ depends significantly on the underheating. The boiling curves have flat sections in the region of small wall superheating, but with higher superheating their relatively small magnitude leads to a sharp increase of the thermal flux density.

In this same figure the results of this present paper are compared with the data of [9] for the boiling of water in the case of transverse flow around a cylinder of stainless steel, and with [10] for water boiling at the surface of a horizontal tube of stainless steel in a large volume and with different underheating values. Comparison with [9] allows one to notice that with very slightly differing values of w and Δt, the thermal flux density corresponding to identical values of superheating, in a system with a fluidized bed, is higher by a factor of ≈ 2. The authors of [10], based on a comparison of the boiling curves with underheating in a large volume and in conditions of forced convection in tubes, draw the conclusion that the curves for surface boiling with forced convection cannot be based on the data for boiling with saturation in a large volume, but rather should be based on actual data for forced convection. Obviously, this conclusion is valid also for the results of the present paper.

Figure 3b shows the experimental points of the boiling curves for different values of the filtration speed and particle sizes of the solid component. It can be concluded that these parameters do not have such a significant effect on the location of the boiling curve as the underheating.

Analysis of the data of the present investigation allows an initial representation to be compiled of the physical pattern of surface boiling in a fludized bed. The particles of the solid component introduce in the boundary layer an additional mass of underheated liquid, which leads to a reduction of superheating of the heat-transfer surface and the boundary layer of liquid and, as a consequence, to deactivation of the steam-formation centers. Moreover, condensation of steam bubbles takes place more intensively because of the turbulent remixing. In these conditions the most active centers of steam formation react but their number is small. However, with increase of superheating, new centers are activated and even a small change in their number makes a significant contribution to the total heat-exchange intensity and the thermal flux density increases sharply. The conclusion drawn is confirmed also by Eq. (6), in accordance with which $\Delta q \sim \vartheta_0^{7.14}$.

NOTATION

d, ρ and ε_0, diameter, density of the material, and porosity of the immobile filling of particles of the component; ε, porosity of the fluidized bed; q, thermal flux density; w, speed of filtration of the fluidizing medium; t, average temperature; ν and λ, coefficients of kinematic viscosity and thermal conductivity of the fluidizing medium; t_{sat}, saturation temperature; $D = 2\varepsilon d/3(1-\varepsilon)$, equivalent diameter of the pore channel; α, heat-transfer coefficient; $Nu = \alpha D/\lambda$, Nusselt criterion; $Re = wD/\varepsilon\nu$, Reynolds criterion; Pr, Prandtl criterion; ϑ, superheating of the heat-transfer surface; ϑ_0, same, in the case of developed surface boiling; Δq, effective thermal flux; m, a power index; $\Delta t = t_{sat} - t_{fl}$, underheating to the temperature of saturation; p, pressure; δ, diameter of the heater. Indices: fl, s, and fm, temperature of the fluidizing medium, the heat-transfer surface, and film.

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FILM BOILING WITH CHEMICAL REACTION ON A VERTICAL CATALYST SURFACE

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A mathematical model is given for the film boiling of a liquid on a vertical catalyst surface. The effect of the parameters of the mathematical description on the process is investigated.

There have been many works and review papers on film boiling on heated surfaces, reflecting the main features of the phenomenon [1, 2]. Exothermal chemical reaction on a catalyst surface between vapors of the vaporizing liquid leads to heating of the catalyst surface and film boiling. An important characteristic of this type of boiling is the dependence of the heat fluxes and the surface temperature both on the rate of the reaction and on the intensity of vaporization processes at the gas–liquid interface. It is of interest to write a mathematical description of laminar film boiling on the vertical surface of a catalyst plate of length L and thickness 2b.

The physical model of the process is shown in Fig. 1, where 2 is the liquid flowing past a vapor film 1 at some constant rate U_∞. As a result of heating of the metal-catalyst surface 3, the liquid vaporizes, and its vapors react on the active catalytic surface, maintaining its temperature at a level sufficient for stable film boiling. In deriving the mathematical description, it is assumed that mass and heat transfer in the vapor film in the longitudinal plate direction occurs as a result of the convective flux and mass and heat transfer in the transverse direction as a result of diffusion and heat conduction and also the transverse component of the vapor velocity.

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