HEAT TRANSFER IN "OBLIQUE" FLOW OF A FLUID WITH $Pr \ll 1$ OVER A SINGLE TUBE

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Experimental data for the heat transfer from a single tube in a flow of fluid with $Pr \ll 1$ at angles of attack in the range 15-80° in a convergent channel are given.

Calculation of heat transfer in the entrance and exit regions of shell-and-tube heat exchangers, coil-type steam generators, and other similar plants requires a knowledge of the heat-transfer coefficients in the case of external flow over tubes at various angles of attack ψ. These questions, however, have still not been adequately investigated and there are very few publications on heat transfer in an "oblique" flow of heat-transfer media with $Pr \ll 1$ [1-4].

In this paper we give the results of investigations of heat transfer from a single tube over which a heat-transfer medium with $Pr \simeq 0.007$ flows at angles of attack $15° \leq \psi \leq 80°$.

As distinct from the traditional experimental technique, where the tube is washed by a parallel flow of liquid, the experimental setup ensured that the angle of attack of the liquid on the tube varied over its length, i.e., there was a closer approximation to real conditions of flow over a tube in the corresponding exchangers. This was achieved by having the working part of the test section constructed in the form of a rectangular convergent channel (cone angle 25°, length 600 mm, entrance section 300 × 80 mm, exit section 50 × 80 mm).

In the channel three tubes (22 × 3 mm in diameter) were installed successively at angles of 20, 40, and 70°, respectively, to the channel axis. This allowed variation of the angles of attack in the ranges $60° \leq \psi \leq 80°$ for tube No. 1, $30° \leq \psi \leq 50°$ for tube No. 2, and $15° \leq \psi \leq 27°$ for tube No. 3. Since the tubes were situated in a convergent flow, for a fixed flow rate the velocity of flow over the tube surface along the streamlines (ψ = const) was different. As a characteristic velocity for a prescribed angle ψ we used the velocity of the liquid in the tube-free cross section of the channel passing through the tube axis.

The ranges of the main experimental parameters were as follows: t_L = 200-250°C, w = 0.03-1.26 m/sec, q = 200,000 W/m^2, Pe = 7-200, ψ = 15-80°, and $Pr \simeq 0.007$.

The working tubes were heated by tubular electric heaters insulated from the walls by insulation with good heat conduction. The surface temperature was measured with movable thermocouples embedded in the tube wall along 12 equidistant generatrices. In this way we measured the temperature distribution over the whole tube surface. From the obtained measurements of t_L, t_W, q, and w we calculated the local and average (over the tube perimeter) heat-transfer coefficients in relation to the velocity and angle of attack ψ of the flow.

The values of the physical parameters in Nu and Pe were taken at the mean flow temperature, and the characteristic length was the tube diameter.

The results of the experiments showed that for all angles of attack ψ the variation of the local heat transfer over the tube perimeter in the corresponding section was similar to that of transverse parallel flow over a single cylinder [1] — maximum variation in the frontal region and minimum variation in the rear region.

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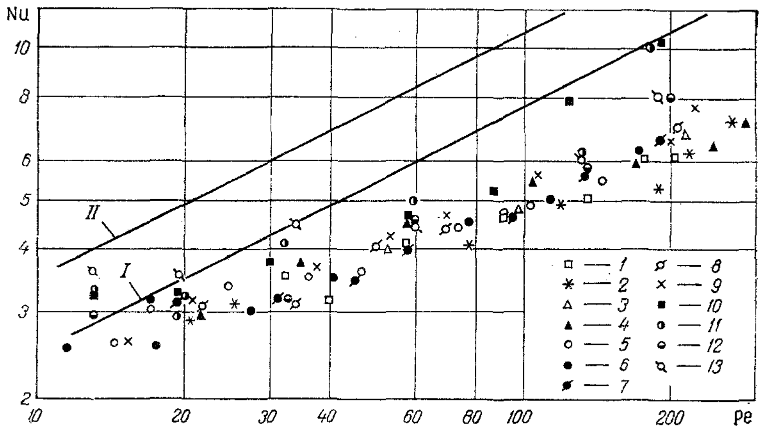

Fig. 1. Relation Nu = f(Pe) for different angles of attack ψ on a single cylinder. Experimental points of this investigation: tube No. 3, ψ: 1) 15; 2) 20; 3) 25; 4) 27°; tube No. 2, ψ: 5) 30; 6) 35; 7) 40; 8) 45; 9) 50°; tube No. 1, ψ: 10) 60; 11) 70; 12) 75; 13) 80°. Theoretical relationships [4]: I) $\psi = 15°$; II) $\psi = 80°$.

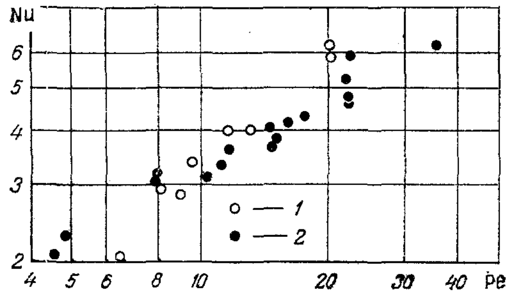

Fig. 2. Relation Nu = f(Pe) for staggered bundle of inclined tubes ($s_1/d = s_2/d = 1.09$; $\psi = 45°$): 1) data of this work; 2) data of [2].

From the conducted experiments we can state that to an accuracy of ±20-30% the angle of attack had no effect on the heat transfer of a single tube under the experimental conditions (Fig. 1).

A comparison of the results with the analytical relationships [1,4] derived from an examination of a potential flow in application to an "oblique" flow of liquid metal over single tubes showed (Fig. 1) that the experimental heat-transfer values lay well below the lines and that the index of the power of Pe in the relation Nu = f(Pe) is about 0.35 instead of the expected 0.5 [1,4]. In view of this we conducted a control experiment, in which we measured heat transfer from one of the investigated tubes (tube No. 2) in the previously tested [2] staggered bundle of inclined tubes ($s_1/d = s_2/d = 1.09$; $\psi = 45°$) in a flow of the same liquid with $Pr \simeq 0.007$.

Figure 2 shows the results of this experiment and compares them with the experimental data of [2]. Figure 2 shows satisfactory agreement of all the experimental data.

Thus, we can conclude from the obtained data that the nature of the relation Nu = f(Pe) in the case of flow of a liquid with $Pr \ll 1$ over a single tube at different angles in a convergent channel differs from that in the case of "oblique" flow over tubes in a bundle.

NOTATION

t_L, flow temperature; w, flow velocity; t_W, temperature of heat-transfer surface; q, specific heat flux; ψ, angle of attack of flow on frontal generatrix of tube; $Nu = \alpha d/\lambda$, Nusselt number; $Pe = wd/a$, Peclet number; α, heat-transfer coefficient; d, outer diameter of tube; λ, thermal conductivity; ν, kinematic viscosity; $Pr = \nu/a$, Prandtl number; a, thermal diffusivity.

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EFFECT OF STATE OF HEAT-TRANSFER SURFACE ON RUPTURE OF THIN FILMS OF BOILING LIQUID

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The effect of roughness of the heat-transfer surface and the presence of a corrosion film on the rupture of stationary films of boiling liquid was experimentally investigated.

The current literature contains hardly any information on the effect of the state of the heat-transfer surface on the rupture of thin boiling liquid films. The known data [1] on the effect of roughness of the surface and the presence of an oxide film on it cannot be extended unreservedly to boiling liquid films.

The generally accepted theories of rupture of thin nonisothermic films [2, 3] ignore the state of the heat-transfer surface.

In this paper we give the results of an experimental investigation of the mechanism of rupture of thin stationary liquid films with highly developed boiling in relation to the roughness of the surface and the presence of a corrosion film on it.

The experiments were conducted on the experimental apparatus described in [4] with distilled water at heat-flux densities of 100-800 kW/m^2 and pressures of 0.1-0.4 MPa on surfaces made of copper, 1Kh18N9T stainless steel, and lead. We compared three kinds of surfaces – a polished surface (treated with diamond paste of grain size 2 μ until a mirror finish was obtained), a technically rough surface [class 5-6 according to GOST (All-Union State Standard) 2.309-68], and a roughened surface (treated with coarse emery paper, class 1-2 according to GOST 2.309-68).

Before the experiments the surfaces were thoroughly washed with ethanol. The polished surface was also boiled for half an hour in butanol, then dried, and washed in ethanol. Experience showed that less thorough treatment of the surface after polishing failed to remove the traces of fat from the diamond paste, which greatly distorted the results of the experiments.

As Fig. 1 shows, surface roughness had no effect on the critical thickness for rupture of a boiling film on a surface made of stainless steel, while the liquid film on copper was more stable on a polished surface, although the difference was not very great (about 20%). Experiments showed that at a pressure of 0.2 MPa surface roughness of any material had hardly any effect.

As we know [4-6], vapor bubbles are the reason for rupture of boiling films. In the case of highly developed boiling the difference in the number of active vapor-forming centers on surfaces prepared in different ways is slight and, hence, the number of potential sites of rupture of the film is almost independent of the roughness. On the viscous copper polishing has a more pronounced effect on the surface relief and, hence, on the number of vapor-forming centers than on a stainless steel surface. Thus, there is less probability of

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