CONVECTIVE HEAT TRANSFER IN A METASTABLE LIQUID WITH DELAYED BOILING

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An analysis is made of the steady-state heat transfer in a large volume of diethyl ether, n-pentane, and benzene with a thin wire immersed. A 90°C superheat was produced at the wire surface, while the bulk liquid remained at saturation temperature.

Instability and delay of the boiling process are particularly noticeable in the case of alkali metals [1, 2]. The mechanism of these phenomena is also responsible for the appearance and the long life of boiling nuclei. In this study we used platinum and nickel wires 29-84 μ in diameter and 60 mm long. Such a wire was immersed in a large volume of liquid and then heated, serving at the same time as a resistance thermometer. It was noted that the liquid in the boundary layer became always superheated while the thermal power was gradually boosted. Boiling is delayed under such conditions and the heat is transmitted then by conduction and natural convection. The bulk liquid may be either subcooled or at saturation temperature T_S. Most tests were performed in the latter mode, under atmospheric pressure in a glass jar. High superheat levels were observed in the liquid near a wire (Fig. 1, curve 1). For diethyl ether, n-pentane, and benzene in our tests the superheat $\Delta T = T_W - T_S$ reached up to 90°C. The temperature drop across a wire did not exceed 0.05°C. As ΔT was raised, there occurred a transition to bubble boiling and this mode continued also under a reduced heat load q.

The attainment of a high superheat under steady-state conditions has made it possible to determine the heat-transfer coefficient and to establish the feasibility of generalizing all test data in terms of the standard criterial relation:

$$\mathrm{Nu} = C(\mathrm{GrPr})^n. \tag{1}$$

The boundary layer of a liquid represents the major thermal resistance and in this case it is metastable, which makes the problem a nontrivial one. It will be assumed here that the thermophysical properties of the liquid may be smoothly extrapolated beyond the saturation line. The validity of the assumption has been confirmed experimentally [3] as regards the specific volume, the compressibility, and the thermal expansivity. The common rule of extrapolation will also be applied to λ, c_p, and ν [4]. Then, by matching calculated values with Eq. (1), we will decide whether the chosen procedure for representing the thermophysical properties of a highly superheated liquid is reliable.

The test results are shown in Fig. 2. The thermophysical properties are referred here to the temperature $T = T_S + (1/2)\Delta T$. On the same diagram we have plotted points 4 for benzene with an 84 μ thin wire but no superheat anywhere in the liquid. These points lie in the same general region. The proper matching of parameter values in Eq. (1) yields C = 1.05 and n = 0.135, which agree closely with the values in [5]. Thus, we have demonstrated the correctness of describing the heat transfer in a metastable liquid in terms of conventional relations and using extrapolated values of its thermophysical properties. We note that local superheating of a liquid occurs also during intensive boiling.

We will examine the transition to boiling along the wires in our experiment. During boiling along thin wires, the dependence of the mean thermal flux density q on the mean-over-the-length temperature excess $\Delta T = T_W - T_S$ ceases to be a uniquely defined relation. Let us consider the simplest case, where two neighboring vapor generating nuclei do not interact and where all nuclei remain identical. We will now

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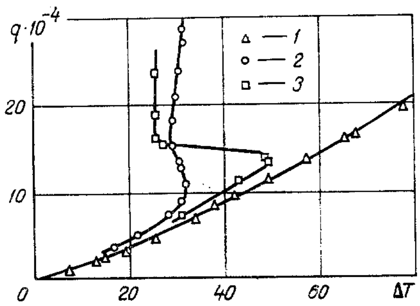

Fig. 1

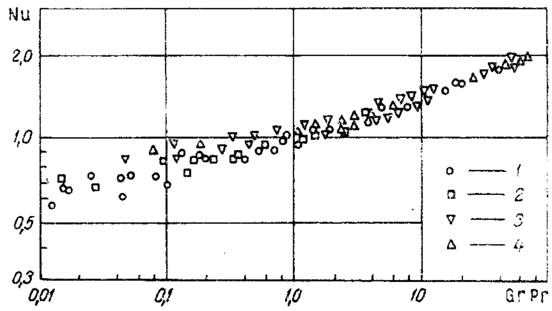

Fig. 2

Fig. 1. Thermal flux density (W/m^2) as a function of the temperature excess (°C), for benzene with a wire 84 μ in diameter: 1) convection; 2, 3) boiling.

Fig. 2. Criterial evaluation of test data on the convective heat transfer in a liquid superheated at a wire surface: 1) diethyl ether; 2) n-pentane; 3) benzene; temperature of liquid equal to the boiling point; 4) convective heat transfer in benzene at $T_W < T_S$.

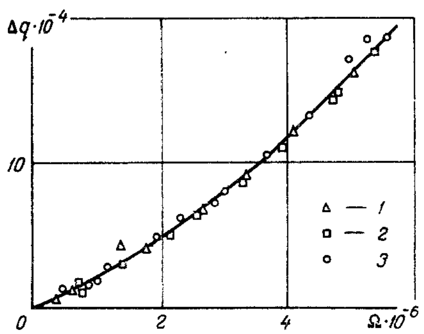

Fig. 3. Increment of thermal flux density Δq (W/m^2) as a function of the density of vapor generating nuclei Ω (m^{-2}): two of the three different boiling curves (1, 2, 3) have been plotted in Fig. 1.

subdivide the wire into segments where specific modes of heat transfer occur: boiling at discrete nuclei or convection. In view of the different nature of these heat transfer modes, the temperature T_{W1} of segments at which convection occurs will be different than the temperature T_{W2} of segments at which boiling occurs. Obviously, $T_{W2} > T_{W1}$. The mean thermal flux density during boiling can be determined from measurements and the relation

$$q = \beta\alpha_2(T_{w2} - T_s) + (1 - \beta)\alpha_1(T_{w1} - T_s).$$

Here $\alpha_2 > \alpha_1$. When the thermal resistance of a wire is a linear function of its temperature, then the mean wire temperature will be related to temperatures T_{W1} and T_{W2} as follows:

$$T_w = \beta T_{w2} + (1 - \beta)T_{w1}. \tag{2}$$

We then have for the mean thermal flux density

$$q = \alpha_1(T_w - T_s) + \beta[\alpha_2(T_{w2} - T_s) - \alpha_1(T_{w2} - T_s)]. \tag{3}$$

Thus, at the same measured mean temperature excess $\Delta T = T_W - T_S$ one may measure many different values of the thermal flux density q which correspond to different fractions β of wire along which boiling occurs (Fig. 1).

Initially β is a small fraction and boiling differs only slightly from convection. At some instant the number of vapor generating nuclei increases sharply and the fraction of wire along which boiling occurs will increase. Then, according to (2) and (3), the mean wire temperature T_W drops and the thermal flux density increases. As a result, the $q = f(\Delta T)$ function becomes S-shaped.

Considering that β is proportional to the number of boiling nuclei N or to their density $\Omega = N/S$, expression (3) can be rewritten as $\Delta q = A\Omega$ with $\Delta q = q - \alpha_1(T_W - T_S)$ denoting the increment of thermal flux density in boiling over convection and A denoting a coefficient which is a function of T_{W2} only. The unique relation between ΔQ and Ω is tracked experimentally, as shown in Fig. 3.

NOTATION

T_W	is the mean wire temperature;
T_{W1}, T_{W2}	are the temperatures of the wire segments at which, respectively, heat transfer by convection and heat transfer during boiling occurs;
T_S	is the boiling point of a liquid;
β	is the fraction of wire along which boiling occurs;
α_1, α_2	are the heat transfer coefficients during convection and boiling, respectively;
N	is the number of vapor-generating nuclei;

S is the total wire surface;

$\Omega = N/S$.

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