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BOILING CHARACTERISTICS OF EMULSIONS WITH A LOW-BOILING DISPERSED PHASE AND SURFACTANTS

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Results of measurement of heat-transfer coefficients are reported for the case of boiling of a dispersed phase of a water–PÉS-5 emulsion on the surface of electrically heated thin platinum wires.

Emulsions with a low-boiling dispersed phase are recommended as heat-removing media. The most pronounced cooling effect can be expected in the case of dispersed phase boiling on a heater and in the liquid layer adjacent to the latter.

We investigated the coefficients of heat transfer from the surface of platinum wires to the PÉS-5 silicone liquid and to the distilled water-in-PÉS-5 emulsion prepared by vigorous stirring of the initial fluids by an agitator. Some experiments were carried out with emulsions prepared by additional breakup of large dispersed droplets of water by an ultrasonic field with a frequency of 22 kHz.

To stabilize the emulsions, 1 vol.% trisodium phosphate or sodium hydroxide was added. These chemical compounds interacted with the PÉS-5 to form surfactants. We did not employ the widely known surfactants, because of their thermal decomposition at high temperatures, which causes contamination of the heat-releasing surface by decomposition products.

In the experiments, we used platinum wires with diameters $d = 0.05$ and 0.10 mm and lengths l of about 50 mm. The wire served simultaneously as a heater and a resistance thermometer. The heat-transfer coefficient was determined by pumping a heat carrier (the emulsion or the fluid PÉS-5) through a glass cylinder 50 mm in diameter, on whose axis a heated wire was fixed [1].

Heat-transfer coefficients were measured for vertical and horizontal positions of the wire and at emulsion temperatures of 30, 40, 50, 60, and 65°C. The investigated emulsions had concentrations of from 0.1 to 8 vol.% of water in the PÉS-5. In the experiments, we measured the current intensity I in the wire, the voltage drop U on it, and temperature of the heat carrier T. The data obtained were used to calculate the specific heat flux $q = UI/\pi dl$ and the effective wire temperature T_w. The temperature drop along the wire and over its cross section were neglected. The heat-transfer coefficient was determined by the formula $\alpha = q/(T_w - T)$.

The dispersion composition of the emulsion was analyzed by the photomicroscopic method. The droplet distribution function F with respect to droplet diameter D is shown in Fig. 1. The distribution $F(D)$ has two maxima: the first pertains to droplet diameters of about 1–2 μm; the second, to diameters of 30–60 μm. Despite a large amount of small droplets, their total volume was not more than 1% of the total volume of the dispersed phase. When the emulsion was subjected to the action of an ultrasonic field, 30–60 μm droplets were broken up to approximately 1 μm.

Figure 2 represents a plot of the heat-transfer coefficient α versus the temperature drop $\Delta T = T_m - T$ for different concentrations of the emulsion. At wire temperatures $T_w < 150°C$, which correspond to $\Delta T < 100°C$, there is a slight difference in the heat-transfer coefficients of the emulsion and the PÉS-5. An increase in temperature T_w causes a drastic increase in α of the emulsion. The maximum α value is attained at temperatures close to that of limiting water superheating ($T_s \cong 300°C$ [2]). A further increase in the wire temperature leads to a crisis of nucleate boiling (not shown in the figure). At low concentrations of the emulsion ($C < 0.3$ vol.%, points 2 and 3

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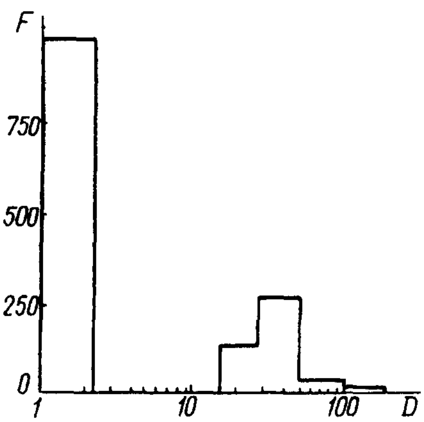


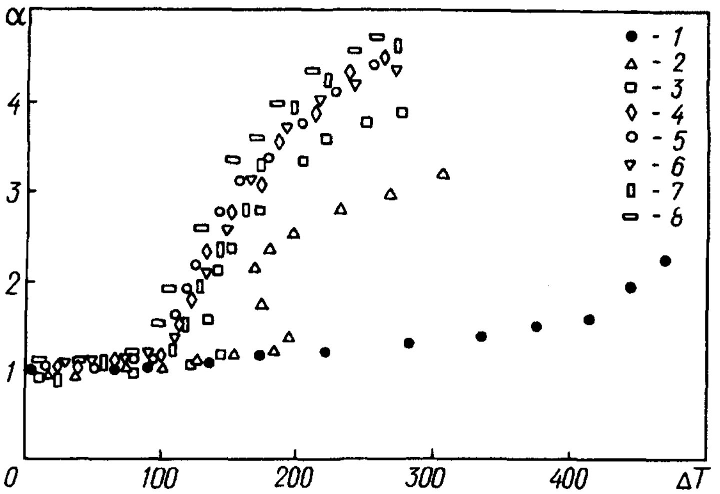


Fig. 1. Histogram of distribution of the number of droplets F (cm^{-3}) with respect to their diameters (μm).

Fig. 2. Heat-transfer coefficient α ($kW/m^2 \cdot {}^\circ C$) as a function of the temperature drop $\Delta T = T_w - T$ (°C): 1) pure PES-5 silicone liquid; 2, 3, 4, 6, 7, and 8) emulsions at different volume concentrations of water in the PES-5: 0.1, 0.3, 0.5, 0.8, 2.0, and 8.0 vol.%, respectively; 5) emulsions prepared in an ultrasound field (C = 1.0 vol.%, T = 50°C).

in Fig. 2) there is observed a delay of the onset of boiling. Water superheating in the emulsion droplets reached 100°C, which was due to the relatively small amount of the low-boiling fraction in direct contact with the heater. The results of the experiments with the emulsions obtained in an ultrasonic field (points 5 in Fig. 2) are nearly the same as the data for the emulsions prepared with an agitator.

In experiments with the water-in-silicone fluid PMS-300 emulsions [3] under convective heat transfer conditions it was found that the heat-transfer coefficient depended on the initial temperature of the emulsion. This was observed near the boiling temperature of the low-boiling fraction. For the emulsion investigated in the present work in the temperature interval T = 30–65°C this effect was not found.

Unlike pure water boiling on the wire, where a boiling crisis is already manifested at $T_w \cong 120$°C, nucleate boiling in the emulsion is delayed. Steady nucleate boiling of water occurs in the dispersed phase of the emulsion at wire temperatures of from 150°C to the temperature of limiting superheating of water. This is attributable to the fact that vaporization in the emulsion proceeds not only on the heating surface but also in the thermal boundary liquid layer adjacent to it. The vapor formed upon boiling is insufficient for formation of a continuous vapor film around the platinum heater. The intensity of heat release in the emulsion increases also as a consequence of the fact that water droplets are easily superheated in the dispersion medium and, boiling up, turbulize the boundary layer.

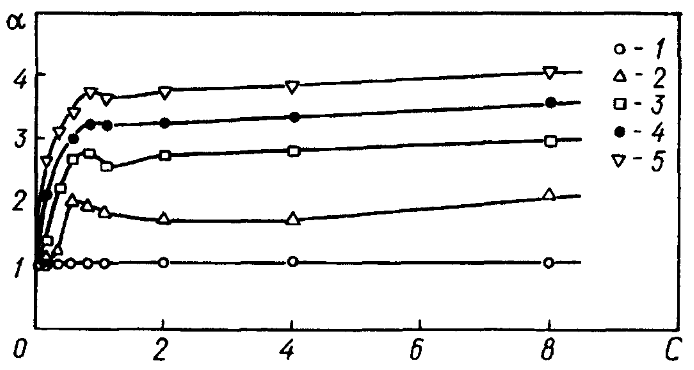
The dependence of α on the water concentration in the emulsion at different ΔT values is shown in Fig. 3. The most pronounced changes in the values of the heat-transfer coefficient of the emulsion are observed in the concentration range of 0–1 vol.%. A further increase in the emulsion concentration to 8 vol.% had practically no effect on heat transfer. The emulsions with higher concentrations were unstable and underwent stratification for two days.

Nucleate boiling of pure liquids is described by the following dimensionless equation [4]

$$\mathrm{Nu} = A\mathrm{Re}^n\mathrm{Pr}^m . \tag{1}$$

Processing of experimental data on nucleate boiling of the emulsion showed that they can be approximated by an equation of the form

$$\mathrm{Nu} = A\,(C)\,(\mathrm{Re}/\mathrm{Pr})^{0.35} , \tag{2}$$



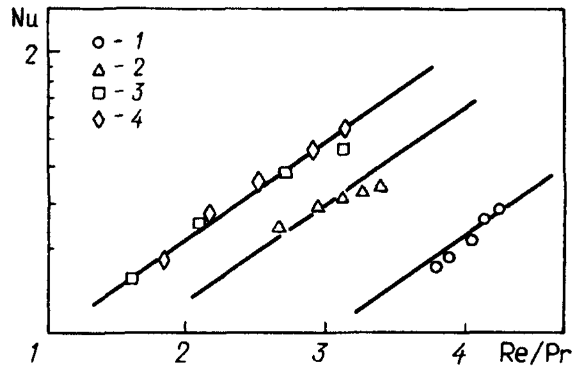


Fig. 3. Heat-transfer coefficient α (kW/m^2·°C) as a function of the concentration C (vol.%): 1) $\Delta T = 90$°C; 2) 120; 3) 150; 4) 175; 5) 200.

Fig. 4. Nusselt number as a function of the complex Re/Pr at different concentrations: 1) $C = 0$ vol.%; 2) 0.1; 3) 1.0; 4) 8.0. Lines – calculation by Eq. (2).

where

$$A = 0.83 + 3.24\,(1 - \exp(-\,0.73C))\,. \tag{3}$$

Values of the parameters ρ'' and r entering the dimensionless Nu, Re, and Pr complexes were taken for the dispersed phase, and values of ρ', λ, C_p, and σ for the dispersion medium. The size of nuclei at the first stage of nucleation is determined by that of the droplets of the dispersed phase of the emulsions. Then the nuclei coalesce and these bubbles determine the character of heat transfer in developed nucleation of the emulsion. The characteristic linear dimension of secondary bubbles leaving the heat-transfer surface and turbulizing the boundary layer is determined as $L = (\sigma/g(\rho' - \rho''))^{1/2}$.

The dependence of the Nu number on Re/Pr in a logarithmic scale is represented in Fig. 4.

Thus, emulsions of the "water–PES-5" type allow enhancement of heat transfer. In the temperature range of 150–300°C, the heat-transfer coefficient of the emulsion is 3–4-fold higher than that in pure water and PES-5. The value of α slightly depends on the dimension of the dispersed phase of the emulsion, increases with the water concentration, and attains limiting values at $C \cong 1$ vol.%. Addition of surfactants to the emulsion exerts an insignificant influence on the heat-transfer rate but greatly influences its storage time without marked stratification.

NOTATION

α, heat-transfer coefficient, W/(m^2·°C); q, specific heat flux, W/m^2; $\Delta T = T_w - T$, temperature drop equal to the difference between the temperature of the heat-releasing surface T_w and that of the heat carrier T, °C; $S = \pi dl$, area of the wire surface, m^2; ρ', ρ'', densities of the liquid and vapor, respectively, kg/m^3; L, characteristic linear dimension, m; g, gravitational acceleration, m^2/sec^2; r, heat of vaporization, J/kg; σ, surface tension, N/m; C_p, heat capacity at constant pressure, J/(kg·°C); λ, thermal conductivity, N(m·sec); C, emulsion concentration, vol.%; Nu, Re, and Pr numbers, dimensionless parameters.

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