EXPERIMENTAL STUDY OF HEAT TRANSFER TO LIQUIDS CONTAINING ADDITIVES OF HIGH POLYMERS AND SURFACTANTS

O. K. Bezyukov, V. A. Zhukov,
and V. A. Larin

Results of investigation are presented on a change in the mean coefficient of heat transfer to water containing small additives of polyacrylic amide and surfactants with variation in the rate and in the thermal head.

The study of the influence of additives of polymers and surfactants on the heat-transfer rate is of both scientific and practical interest. Currently there are many publications devoted to this problem, which contain results of experimental investigations showing that small additives of polymers and surfactants may lead to an increase or a decrease in the heat-transfer rate.

Work [1] gives the data of experiments obtained during turbulent flow along a horizontal tube of weak solutions of high polymers: polyacrylic amide (PAA) (c = 0.012%) and polyethylene oxide (c = 0.007%) testifying to the fact that the addition of polymers to water can reduce the heat-transfer coefficient by 5-6 times. In the same work it is also noted that during circulation of solutions along a closed loop their specific features are gradually lost because of destruction of polymer molecules. In the polyethylene oxide solution they soon practically disappear completely, while in the PAA solution (which is more stable) under prolonged circulation conditions the decrease of the heat-transfer coefficient is retained at a level of 40%.

Analogous data are obtained for a turbulent flow mode in a horizontal tube of solutions of surfactants [2], for which we observe a decrease in the heat-transfer coefficient by 38% but at considerably lower concentrations (c = 0.16%) as compared to high polymers. The mechanism of decreasing the heat-transfer rate in the turbulent flow of the solutions of surfactants and polymers as well as its connection with the reduction of hydrodynamic resistance and with the decrease in turbulent pulsations of the rate and temperature are considered in detail in [3-6].

The authors of [7] present the results of investigation of heat transfer to the polymer solutions in boiling under natural convection conditions that indicate an increase in the heat-transfer rate. Experiments on heat transfer during boiling of surfactants solutions in the horizontal tube were conducted in [8]. In that case the increase of the heat-transfer coefficient amounted to 1.5-2 times in comparison with pure water. Heat transfer enhancement under boiling conditions, when adding polymers and surfactants, was also noted in [9].

The growth of the heat-transfer coefficient during boiling in the presence of additives is explained by their effect on physical properties of the liquid, first of all, on the surface tension and wettability of the heat-transfer surface. Surfactants are also the catalyst for the process of nucleation of vapor bubbles [2].

All the available publications consider the effect of additives with definite character of heat transfer: either convective under turbulent flow conditions or under saturated bubble boiling.

In a number of technical systems, e.g., in systems for diesel cooling, the liquid circulation rate and thermal loads vary within wide limits; this causes the presence of regions having different heat transfer characters.

The aim of the present investigation was to estimate the effect of the indicated additives on the heat-transfer coefficient depending on the liquid circulation rate at its various temperatures and thermal loads. The studies were performed using solutions of polyacrylic amide (whose mass concentrations at 20°C comprised 0.01 and 0.02%), solutions of surfactants (Sintakol DS-10 with mass concentrations of 0.05 and 0.1%), a solution containing 0.02% polyacrylic amide and 0.05%
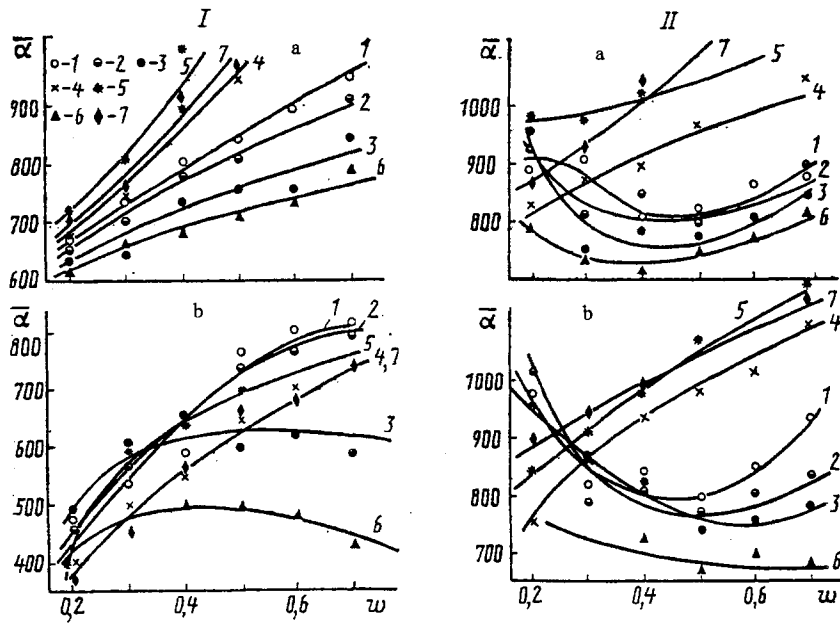

Fig. 1. Dependence of the heat transfer coefficient $\bar{\alpha}$ (W/(m²·K)) on the flow rate w (m/sec) during heat transfer without boiling (I) and with boiling (II): a) t'_{fl} = 60°C, b) 80°C; 1) water, 2) water + 0.01% PAA, 3) water + 0.02% PAA, 4) water + 0.05% surfactants, 5) water + 0.1% surfactants, 6) water + 0.02% PAA + 0.05% surfactants, 7) water + complex additive.

surfactants, and the solution of the addition consisting of surfactants and corrosion inhibitors of ferrous and monferrous metals with an overall mass of 0.3%. The viscosity of each of the liquids being studied was determined by a VPZh capillary viscosimeter at liquid temperatures of 20 and 70°C.

The experimental setup was a closed loop including a horizontal tube, a reservoir with the liquid in question, and a circulating pump. The horizontal brass tube with an internal diameter of 14 mm had a working section of length $50d_{in}$ (on which the measurements were carried out) and a preinserted section of hydraulic stabilization with a length $20d_{in}$. The working section of the tube was heated by an electrical coil wound on it. The change in tension, supplied onto the coil, allows one to provide different thermal loads. To reduce thermal losses into the air, the tube was covered with a heat-insulating coating. The mean wall temperature t_w was defined by readings of five chromel-copel thermocouples uniformly arranged along the tube length. Readings of the thermocouples were taken by a V7-27A/1 digital voltmeter. The liquid temperature at the tube inlet was sustained with an accuracy up to 0.1°C by a thermostat which served as a reservoir for the liquid. The circulation rate was controlled by the change in the liquid flow rate through the valve and was measured by a differential manometer being calibrated by a weight method for the each liquid under study. The flow rate of liquids along the tube varied from 0.2 to 0.7 m/sec. The calculation of the Reynolds numbers for the given rates taking the measured viscosities into account showed that for all the liquids (as the flow rate in the tube increases), a transition from the laminar flow mode to the developed turbulent one takes place.

The tests were carried out with two liquid temperatures at the tube inlet (60 and 80°C) and two regimes of tube heating:

1) excluding the near-wall boiling onset ($t_{wmax} \approx 90°C$);

2) providing the presence of sections with near-wall boiling ($t_{wmax} \approx 135\text{-}140°C$).

On performing the tests, we determined the heat-transfer coefficient α_F by the steady heat flux method on the basis of the Newton-Richman law [10].

$$dQ = \alpha_F(t_w - t_{fl})\,dF. \tag{1}$$

In going to the mean heat-transfer coefficient along the tube length $\bar{\alpha}$, as a consequence of simple conversions of expression (1), we obtain the predicted formula

$$\bar{\alpha} = \frac{c_p \rho d_{\text{in}} w (t''_{\text{fl}} - t'_{\text{fl}})}{4l \left(\dfrac{1}{n} \sum\limits_{i=1}^{n} t_i - t_{\text{fl}} \right)}, \quad \text{W/(m}^2\text{·deg)}.$$

(2)

The results of investigation are presented in the form of dependences of the mean heat-transfer coefficient on the circulation rate for liquids of different compositions. For comparison the dependences obtained during studies performed in a tube of water not containing additives were taken.

In heat transfer without boiling (Fig. 1, I) at small flow rates (w = 0.2-0.3 m/sec), corresponding to the laminar regime and to the onset of the transition to the turbulent flow, the values of the heat-transfer coefficients in liquids of different compositions are distinguished between themselves insignificantly. This is explained by the fact that the high polymer molecules and micellar formations of surfactants, orienting along the flow, do not affect the flow pattern and the flow structure. By increasing the rate and passing to the developed turbulent flow conditions, we have not obtained significant differences in the heat-transfer coefficients for solutions containing surfactants, additives, and 0.01% PAA. The essential decrease in the heat-transfer coefficient at high rates (w = 0.6-0.7 m/sec) was observed for the 0.02% solution of PAA; it composed 9-18% at $t_{\text{fl}}' = 60°C$ and 31-44% at $t_{\text{fl}}' = 80°C$. The still more decrease in the heat-transfer coefficient took place for the solution, containing 0.02% PAA and 0.05% surfactants, i.e., 16-18% at $t_{\text{fl}}' = 60°C$ and 40-49% at $t_{\text{fl}}' = 80°C$. Here, probably, the synergetic effect of the simultaneous influence of high polymer molecules and surfactant micelles manifested itself. The values for the standard head ΔT for all the liquids were practically identical.

During heat transfer in the case of boiling (Fig. 1, II), the character of the influence of the introduced additives is independent of the liquid temperature at the tube inlet as in the case of heat transfer without boiling.

The greatest coefficient of heat transfer to water corresponds to the rate of 0.2 m/sec, when intensive boiling occurs in the tube and a considerable part of the heat is transferred by vapor bubbles. Then, with an increase in the flow rate, convective heat transfer begins to play a greater role and the heat-transfer coefficient decreases. During further growth of the rate, flow turbulization, and convection intensity it begins to rise.

For the polyacrylic amide solutions at small rates (w = 0.2 m/sec) we obtained an increase in the heat-transfer coefficient of 7-8%, caused by the reduction of the surface tension in the solutions and by more favorable conditions for formation of vapor bubbles. At high rates (w = 0.6-0.7 m/sec), when the convective heat transfer in the turbulent flow begins to prevail, the heat-transfer coefficient decreases by 7-16% for the solution, containing 0.02% PAA and by 17-25% (at $t_{\text{fl}}' = 80°C$) for the solution, containing 0.02% PAA and 0.05% surfactants.

The solutions of surfactants and additives have the character of the $\alpha = f(w)$ relation. At a rate of 0.2 m/sec the values of the heat transfer coefficients for these solutions and for water are insignificantly distinguished. With an increase in the rate, the distinction also increases. At the turbulent flow mode (w = 0.6-0.7 m/sec) the heat-transfer coefficient to the surfactant solutions and to the solution, containing the additive, exceeds its value for water by 22-30% and by 25-34%, respectively. The more intensive heat transfer to the solutions is explained by the fact that when the convective heat transfer already predominates in water, then a considerable part of heat in the surfactant solutions is transferred as before by vapor bubbles.

Comparison between the values for thermal heads ΔT has shown that only the PAA solution (c = 0.02%) at rates of 0.5-0.7 m/sec has an essential distinction from the values for water. The increase of the thermal head by 2-3°C for the PAA solution is explained by the near-wall layer laminarization and is consistent with the reduction of the heat-transfer rate.

When performing the tests, we carried out 5-7 parallel measurements at each experimental point; this allows us to determine the root-mean-square deflections of the values being measured and to calculate the experimental error, which amounted to 2-8%. Large error values correspond to small circulation rates and are related to irregular liquid supply and to large spread in the heat-transfer coefficient during the intensive boiling in the tube.

To perform visual examinations, after the working section of the tube we installed a glass observation pipe, which made it possible to study the character and specific features of the flow.

During circulation of water without additives, vapor bubbles developed only at a rate of 0.2 m/sec and maximal tube heating. Their size was dependent on the liquid temperature at the tube inlet: 2-3 mm at $t_{\text{fl}}' = 60°C$ and 4-5 mm at $t_{\text{fl}}' = 80°C$. The bubbles travelled with intervals from 2 to 5 sec. The flow of the PAA solutions was not visually practically different from that of water without additives.

The solutions, containing surfactants in various concentrations, looked different during the experiments. At rates of 0.5-0.7 m/sec the given liquids were milk-white in color because of an abundance of the smallest gaseous bubbles being in them and continuously moving.

On decreasing the rate, small bubbles merged with the coarser ones; this resulted in that their quantity was lowered and that the liquid acquired transparency. At the 0.3 m/sec rate coarse bubbles of length to 10-12 mm with an interval of 3-5 sec and a great quantity of small bubbles with diameters to 1 mm moved in the flow. The decrease in the rate up to 0.2 m/sec caused the complete disappearance of small bubbles and the further growth of coarse bubbles, whose length at some time instants reached 20 mm. The intervals of bubbles travelling were dependent on the wall temperature and on the inlet liquid temperature and comprised at $t_w < 100°C$ from 5-10 (at $t_{fl}' = 60°C$) to 2-3 sec (at $t_{fl}' = 80°C$); at $t_w > 100°C$ from 2-5 (at $t_{fl}' = 60°C$) to 1-2 sec (at $t_{fl}' = 80°C$).

The visual observation shows that the addition of surfactants to water leads to intensive formation of vapor-gas bubbles in the flow and to increase in their quantity. If during pure water circulation under boiling in the tube we observed a transition from the single-phase flow mode to the bubble one, then during boiling in the tube of the surfactant solution, we observed a transition from the bubble flow mode to the bubble-slug and to the slug (at w = 0.2 m/sec). The visual observations confirm that the more intensive heat transfer process in the presence of surfactants is explained first of all by a change in the character and in the flow mode.

The investigations carried out allow us to draw the following conclusions:

1. Additives to cooling liquids for technical devices (primarily, for diesels) containing surfactants and polymers may exert a considerable effect on heat-transfer processes, therefore, when applying them, we must take this into account.

2. The character of the influence of the indicated additives depends on the liquid circulation rate and on the thermal head. Additives intensify heat transfer in the most thermally stressed regions, where near-wall boiling takes place, and decrease it in regions of heat transfer without boiling.

3. Additives may be used for optimization of the temperature state of heat-transferring surfaces.

NOTATION

c, mass concentration of a substance; d_{in}, internal tube diameter; α_F, local heat-transfer coefficient; dF, area of the heat transfer surface element; dQ, heat flux passing through the surface element; t_w, $\bar{t}_w$, local and mean wall temperatures; t_{fl}', t_{fl}'', cross-sectional mean liquid temperature at the tube inlet and outlet; $t_{fl} = (t'_{fl} + t''_{fl})/2$, mean flow temperature; ΔT, temperature head; $\bar{\alpha}$, mean tube length value of the heat-transfer coefficient; c_p, specific isobaric heat of liquid; ρ, liquid density; w, liquid flow rate along the tube; l, tube length; t_i, wall temperature at the point of arrangement of the i-th thermocouple; n, number of thermocouples.

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