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HEAT TRANSFER IN POOL BOILING OF PROPANE UNDER THE CONDITIONS OF DIFFERENT SATURATION PRESSURES

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The author presents results of an experimental investigation of heat transfer in pool boiling of propane on single horizontal tubes with a polished surface and with a porous coating under the conditions of different saturation pressures. It is shown that the effect of the pressure on the intensity of the heat transfer manifests itself differently on smooth and porous surfaces and depends on the heat-flux density; however this dependence is not monotonic.

Introduction. It is known that the magnitude of the heat-transfer coefficients in boiling of a liquid depends on the pressure, an increase in which leads to intensification of the heat transfer, with the degree of influence of the pressure manifesting itself differently, depending on the type of heat-exchange surface and the thermophysical properties of the liquid. The works published on this subject consider the effect of the pressure in the system on the heat-transfer characteristics in boiling of water, ethanol, Freons, and acetone under different thermal loads [1-4].

There are comparatively few data published on boiling of propane; they are of a limited nature [5-9]. They are basically descriptions of results of investigations of the process for a single value of the pressure; among the works mentioned, only work [9] presents findings of experiments under the conditions of different saturation pressures.

Interest in the processes of heat transfer in boiling of hydrocarbons is due to the needs of the chemical industry and refrigeration engineering. Boiling of propane and other hydrocarbon liquids in the intertube space of heat-exchangers-evaporators is used to obtain cold in installations for liquefaction of natural gas. To ensure operating regimes with minimum energy consumption of the heat-exchange equipment, it is necessary to study the effect on the heat-transfer intensity of the conditions under which the boiling process occurs.

Effect of the Pressure on Boiling Heat Transfer. In experiments of Yu. A. Kuzma-Kichta et al. on boiling of water on a 40 × 10 × 0.5 mm stainless-steel plate with a coating deposited by the method of powder metallurgy [1], heat transfer on the surface with a porous coating was lower at some pressures and thermal loads than on the surface without a coating. In [2], it is noted that under a certain thermal load $q = q^*$ that depends on the structural characteristics of the coating and its thickness the heat-transfer intensity becomes self-similar relative to the pressure for each investigated liquid (the boiling of water, ethyl alcohol, acetone, and DEF fluoroorganic liquid dielectric was studied on copper disks 30 mm in diameter with a sintered metal-fiber capillary-porous structure). Hongji and Aihua [3] conducted experiments on boiling of ethanol and Freon-11 on the exterior surface of copper cylinders 30 mm in diameter with a porous coating of sintered bronze particles. Depending on the thermophysical properties of the investigated liquids and the thermal load, a pressure increase in the system fostered intensification of heat transfer either throughout the investigated range of pressures (Freon-11) or up to a certain value of it, after which the heat-transfer coefficient began to decrease (ethylene).

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The authors of the above-mentioned investigations relate the behavior of the curves $\alpha = f(p)$ to the change in the ratio of the characteristic dimension of the pores on the heat-exchange surface to the critical radius of a bubble R_{cr} that corresponds to the onset of boiling. As R_{cr} decreases with increase in p, the number of working pores increases, causing the heat-transfer coefficients to increase. However, when the heat-flux densities are rather high, a predominant part of the potential nucleation centers is already involved in work on generating bubbles, and a further increase in the pressure does not result in intensification of the heat transfer. Moreover, the gradual change in the thermophysical properties of the liquid due to the pressure increase leads to weakening of other factors favorable to boiling, and there can be a tendency toward a decrease in the coefficients α. According to data of [3], boiling curves that correspond to different pressures merge at high q. A similar result is described in many works on the boiling of liquids investigated most extensively.

Experiment. We present below results of an experimental investigation of boiling heat transfer of propane on single horizontal tubes of stainless steel 1Kh18N10T (the outside diameter is 20 mm, the length is 100 mm) in the range of saturation pressures $p = 3.45-13.8$ bar. The experiments were conducted on a setup [10, 11] that incorporates a stainless-steel boiling chamber with a working section and a condenser, a vacuum-treatment and charging system, and a measuring system that permits computer processing of information. For visual observations and photography of the process, the boiling chamber is equipped with illuminators. To prevent heat transfer to the ambient medium, the boiling chamber is placed in a climatic chamber with a circuit for pumping a cooling or heating liquid. In the investigations described, the temperature in the climatic chamber was maintained equal to the saturation temperature of propane; its magnitude can be prescribed from −20 to +60°C depending on the experimental conditions. The saturation state of the liquid was ensured by changing the condenser's capacity. The heat flux to the specimens was supplied from an electric heater; temperature measurements were performed using copper-constantan thermocouples. The saturation temperature was determined by four absolute thermocouples placed in the liquid and the vapor space and was controlled by a standard manometer. The temperature difference between the heating surface and the liquid was measured directly by four differential thermocouples, one junction of which was located on the specimen and the other in the liquid. The temperature measurements were performed in a steady-state regime.

Boiling was carried out on surfaces without a coating and with a porous coating deposited by the method of gas-thermal spraying. This type of coating is characterized by high heat-transfer efficiency and, which is quite important, manufacturability. We used a wire 1.6 mm in diameter made of steel 40Kh13 as the starting material for spraying. Prior to coating deposition the tubes were cleaned and the surface was shot-blasted. The coating structure was analyzed using scanning and transmission electron microscopes. The investigations were performed on specimens with different porosity ε (4–13%) and porous-layer thickness δ (0.1–0.3 mm).

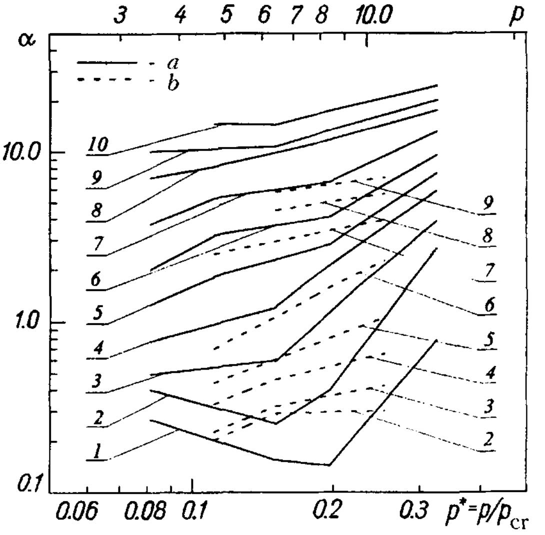
The heat-transfer coefficient was calculated with respect to the exterior surface of the tube without a coating F_{sm}:

$$\alpha = \frac{Q}{F_{sm}\,(T_s - T_{liq})}, \tag{1}$$

where Q is the heat flux determined as the supplied electric power with allowance for heat losses.

Investigation Results. Figure 1 presents the heat-transfer coefficients α as functions of the pressure in boiling on a specimen with a 0.3-mm-thick sprayed layer with a porosity of 12.8% and on a polished tube without a coating (R_z = 1.3 μm). It is seen that the effect of the pressure on the heat transfer manifests itself differently on the smooth and porous surfaces and under different thermal loads.

The negative-slope portions of curves 1 and 2 for $q = 0.2$ and 0.5 kW/m^2 for specimens with a porous coating correspond to a convective regime of heat transfer, which is well seen in comparing these plots with the dependences $q(\Delta T)$ in Fig. 2. Before the onset of boiling, the temperature superheating ΔT of the boiling surface relative to the liquid increases with the thermal load; subsequently, with activation of the first nucleation centers, the temperature difference decreases sharply, after which ΔT continues to increase.



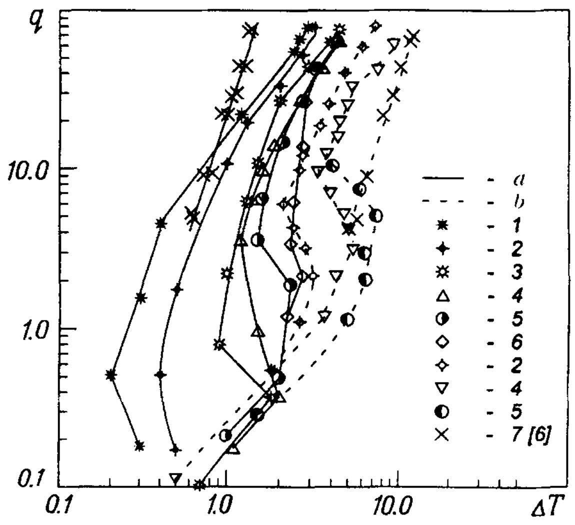


Fig. 1. Heat-transfer coefficients vs. pressure: a) surface with a porous coating; b) smooth surface; 1) q = 0.2 kW/m^2; 2) 0.5; 3) 1; 4) 2; 5) 3; 6) 5; 7) 10; 8) 20; 9) 30; 10) 63.5. α, kW/(m^2·K); p, bar.

Fig. 2. Curves of boiling: a) specimen with a porous coating, b) with a smooth surface; 1) p^* = 0.324; 2) 0.254; 3) 0.197; 4) 0.15; 5) 0.111; 6) 0.081; 7) 0.003 [6]. q, kW/m^2; ΔT, K.

For comparison, Fig. 2 presents results of [6] on propane boiling on vertical tubes 25 mm in diameter made of stainless steel 1Kh18N10T without a coating and with a porous layer of powder of the same steel (the coating was deposited by the method of thermal-diffusion sintering). The slope of the dependences $q(\Delta T)$ for a smooth surface considered in this paper and that obtained by Dvoiris et al. [6] approximately coincide; the curve from [6] is shifted to the region of higher ΔT, which is attributable to a lower (p^* = 0.003) pressure in the system in the experiment. The results of [6] correspond to the regime of developed boiling; the regularities of the process on smooth and porous surfaces are identical; in boiling on porous surfaces, the curve is shifted to the region of small ΔT practically in parallel. In our experiments, there were three regimes of heat transfer: free convection, undeveloped boiling, and developed boiling, which was embodied in the characteristic bends of the curves, and the dependences $q(\Delta T)$ for the smooth and porous surfaces are more complex in character than in [6].

Discussion of the Results. The behavior of the curves $\alpha(p)$ has significant differences from the behavior of the curves obtained in [1-3]. Similarly to the experimental data of the other authors, we observed a weakening of the dependence of the heat-transfer intensity with increase in q; however, the self-similarity of the coefficients α relative to the pressure considered in [2] did not occur. Unlike the experiments of [1], the heat-transfer characteristics of a smooth surface did not exceed the heat-transfer coefficients on a tube with a porous coating for any combination of the pressure and the thermal load. As is seen from the series of curves, the heat-transfer intensity on the porous specimen was much higher in all the investigated regimes of boiling. The dependences $\alpha(p)$ do not have the maxima noted in [3] in boiling of ethanol and in some experiments on Freon-11. The difference in the results is attributable to a number of reasons: differences in the properties of the liquids and the characteristics of the heat-exchange surfaces and noncoincidence of the investigated pressure ranges. To compare the results, it is better to consider the heat-transfer coefficients as functions of the reduced pressure p^* rather than of the absolute pressure (recalculation of the pressures relative to p_{cr} shows that in [1] the working range of the reduced pressures in boiling of water was 0.004–0.267; in [2], $4\cdot10^{-4}$–$4\cdot10^{-3}$ for water, 0.002–0.021 for acetone, and $1.5\cdot10^{-3}$–$1.5\cdot10^{-2}$ for ethanol; in [3] the boiling of ethanol was investigated at p^* = 0.015–0.092 and of Freon-11 at 0.023–0.137).

The porous coating made the heat transfer substantially more intense over the entire investigated range of pressures and heat-flux densities. A pressure increase fostered an earlier onset of boiling, while at $p^* > 0.2$ we were unable to record a regime of free convection on the surface with a porous coating. As the thermal load increased, the dependence of the heat-transfer coefficients on the pressure on the smooth surface became weaker and the slope of the curves $\alpha(p)$ in Fig. 1 decreased. In boiling on the specimen with a porous coating, the effect of the pressure on the heat-transfer characteristics also depends on q but this dependence is not monotonic. In the regime of developed boiling, an increase in the heat-flux density, as in the case of a smooth surface, decreased the effect of the pressure; on some portions of the curves $\alpha(p)$ their position is close to horizontal; however, at pressures p^* higher than ~0.15–0.2 the heat-transfer coefficients begin to increase substantially. On this portion of the horizontal axis there is a slight tendency toward convergence of the curves $\alpha(p)$, which, in logarithmic coordinates, are almost parallel (the dependences of the coefficients α on the pressure in boiling of water in [1] are also parallel, and in the region $p^* \sim 0.04$ there is a bend of the curves in the direction of an increase in their slope relative to the X axis). In Fig. 2, the dependences $q(\Delta T)$ that correspond to reduced pressures lower than ~0.2 begin to merge together at high q; at higher pressures, this does not occur.

A similar character of the effect of the pressure on the intensity of the heat transfer was observed in boiling of propane on single horizontal copper tubes with the regular microgeometry of a Gewa-T-x type surface [9] (T-shaped microfins with a height of 1.04 mm; the step is 1.35 mm, the gap is 0.23 mm, and the diameter of the tube at the base of the fins is 12.48 mm; on the tube surface small depressions are made between the fins to produce additional nucleation centers). In this investigation, at high heat fluxes with increase in q and the saturation pressure the increase in the coefficients α almost ceased; however after attaining a pressure p^* higher than ~0.25 the growth in the intensity of the heat transfer with the thermal load remained at least equal to or even exceeded the same characteristic obtained at lower reduced pressures. In experiments at high pressures, P. Sokol et al. [9] observed two main sizes of the vapor bubbles on the specimens' surface: many small bubbles that were growing over the entire surface of the tube and much larger "secondary" ones that floated up from the surface out of the interfin gaps. At low pressures only very large "secondary" bubbles separated from the investigated tube from the interfin gaps, and practically the entire exterior surface of the fins was free of bubbles. In the opinion of P. Sokol et al. [9], the increase in the intensity of the heat transfer results from activation of potential nucleation centers on the exterior surfaces of the fins, which occurs at p^* higher than ~0.25.

This development of the process on the finned surface is quite logical: the best conditions for operation of nucleation centers occur on the surface in the interfin space (higher superheatings of the liquid at the base of the fins and the presence of the artificial depressions in this zone on the Gewa-T-x surface), and as the pressure increases, the magnitude of the critical radius of the vapor nucleus decreases and vapor generation previously begins on inactive microdepressions of the exterior surface of the fins, which turn out to be quite heated at high q due to the high thermal conductivity of copper.

The results of our investigation are obtained on a heating surface of a different type and a different material; however, the regularities of the pressure's effect on the heat-transfer coefficients are similar. This seems to be due to the change in the critical radius R_{cr} of the vapor nuclei [12]:

$$R_{\mathrm{cr}} = \frac{2\sigma T_{\mathrm{sat}}}{r\rho_{\mathrm{v}}\Delta T}. \qquad (2)$$

Perhaps this was also due to the change in the separation diameter d_0 of the vapor bubbles.

In boiling on the specimens with a sprayed coating under the conditions of different pressures the visual picture, unlike the process on the Gewa-T-x surface, did not undergo substantial qualitative changes. Intense boiling at high thermal loads resulted in shielding of the tube's surface by the rising vapor bubbles gliding over it, which hindered heat transfer. It was impossible to judge the change in the size of the separation diameter of the bubbles as the pressure increased, since vapor accumulations, not primary bubbles, were observed.

In his work V. I. Tolubinskii [12] considered the effect of the pressure on the bubbles' separation diameter d_0 and other internal characteristics of boiling of saturated liquids and drew the conclusion that for a number of liquids d_0 varies approximately in inverse proportion to the pressure. The quantity d_0 also decreases as the density of nucleation centers $n = N/F$ increases, which was noted in [13, 14], and the density n increases in connection with the decrease in R_{cr} as the pressure increases. We can assume that the decrease in d_0 with increase in p^* led to a decrease in the degree of shielding of the heat-exchange surface; this fostered an improvement in the heat-transfer conditions.

Conclusion. Unfortunately, it has not been possible, using reference literature, to establish the thermophysical properties of propane and the regularities of their change as a function of the temperature or the pressure within the range of these parameters employed by us, and therefore it has not been possible to determine their effect on the intensity of heat transfer under the conditions under which the data considered were obtained. In this connection, the role of experimental study of this process increases. It is necessary to continue research in this direction on specimens with a wide range of structural characteristics of the porous coatings.

The results can be used in designing heat-exchange equipment for various branches of technology.

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NOTATION

d_0, separation diameter of the vapor bubble; F, surface area; F_{sm}, area of the surface without a coating; N, number of nucleation centers acting on the heat-exchange surface; n, density of the nucleation centers; p, pressure; $p_{cr} = 42.64$ bar, critical pressure; $p^* = p/p_{cr}$, reduced pressure; Q, heat flux; q, heat-flux density; R_{cr}, critical radius of the bubble; R_z, roughness of the surface; r, heat of vaporization; T_{liq}, liquid temperature; T_{sat}, saturation temperature; T_s, temperature of the heat-exchange surface; $\Delta T = T_s - T_{liq}$, superheating of the heat-exchange surface relative to the liquid; α, heat-transfer coefficient; δ, porous-layer thickness; ε, porosity; ρ_v, vapor density; σ, surface tension of the liquid.

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