S_x, area of liquid in the section x; R, radius of the inner cylindrical surface; R_0, initial radius of the conical surface; l, length of the pipe; $\varphi_{30}, \varphi_{3l}, \varphi_{3x}, \varphi_3^0$, half-angles of flooding in the sections x = 0, x = l, and in an arbitrary section x, and also for $\beta = 0$, respectively; $\overline{\delta}_x = S_x/2\pi R$, mean thickness of the layer of liquid in the section x; $\overline{\delta} = V/2\pi Rl$, mean thickness of the layer of liquid in the pipe; $p = l/R$; $\overline{\Delta} = \overline{\delta}/R$; $A = (\sigma/\rho g R^2)^{1/2}$, dimensionless capillary constant; $\xi = \delta_m/\overline{\delta}$, ratio of the maximum thickness to the mean thickness of the layer; φ_m, angular coordinate of the maximum thickness of the layer; $Re_x = \omega(\overline{\delta}_x)^2/\nu$, Reynolds number in the section x; $Fr_c = \omega^2 R/g$, centrifugal Froude number; $Ca = \omega R\mu/\sigma$, capillarity number; σ, specific surface energy.

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HEAT TRANSFER TO TURBULENT STREAM IN PIPES UNDER SUPERCRITICAL PRESSURES

N. L. Kafengauz

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Experimental results are presented on heat transfer to several liquid hydrocarbons under supercritical pressures and pseudoboiling conditions. An empirical relation is proposed which generalizes these results.

Much attention has been paid in recent years, in the Soviet Union and abroad, to studies of heat transfer to liquids under supercritical pressures. This interest is being stimulated on the one hand by practical considerations, and on the other hand by the desire of scientists to understand the laws of heat transfer under conditions where the physical properties of liquids vary. Reviews of studies on this subject can be found in articles by B. S. Petukhov [1, 2], W. Hall and J. Jackson [3], and V. M. Eroshenko and L. A. Yaskin [4]. Many of those studies have dealt with heat transfer under supercritical pressures with attendant self-excited thermoacoustic vibrations [3, 5, 6]. The effect of these factors will not be dealt with in this report.

On the basis of the results of such studies, there have been proposed many theoretical methods for calculating the heat transfer (Dreisler, Goldman, Petukhov, Popov, Melik-Pashaev, Eroshenko and Yaskin, etc.), and semiempirical formulas have been proposed (Miropol'skii and Shitsman, Krasnoshchekov and Protopopov, etc.) which agree satisfactorily with experimental data on water, carbon dioxide, helium, and other liquids.

Curves taken from one report [1], depicting the $\alpha/\alpha_0 = f(T_w/T_m)$ relation for carbon dioxide, are shown in Fig. 1. The graph indicates that the intensity of heat transfer decreases with rising temperature of the pipe wall. The trend of this relation is the same here as in the methods proposed by other authors and used for other liquids.

Those methods of calculation assume that the mechanism of heat transfer under supercritical pressures is similar to that of plain heat transfer in a turbulent stream of liquid. The difference between them lies essentially in the way of accounting for the variation of properties of a liquid over the stream section. The attenuation of heat transfer with increasing referred wall temperature T_w/T_m is caused by formation of a gaseous boundary layer with a thermal resistance much higher than that of the liquid. The most significant factor affecting this attenuation of heat transfer with rising wall temperature is the change in density, which follows clearly from the theoretical equation $\alpha/\alpha_0 = (2/\sqrt{\rho_L/\rho_w} + 1)^2$ according to S. S. Kutateladze and A. I. Leont'ev.

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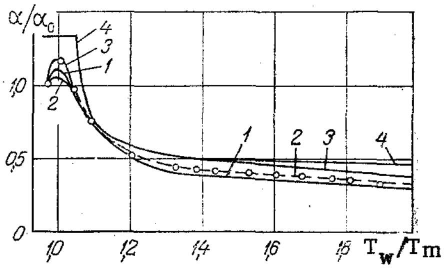

Fig. 1. Dependence of α/α_0 on T_w/T_m during heat transfer to carbon dioxide ($T_m = 317°K$, $T_L/T_m = 0.96$, $p = 98$ bar, $G = 100$ kg/h, $d = 4.08$ mm): 1) theoretical calculation according to V. N. Popov; 2) empirical curve according to E. A. Krasnoshchekov and V. S. Protopopov; 3) empirical curve according to Swenton, 4) empirical curve according to Z. L. Miropol'skii and M. E. Shitsman; dots represent test points.

According to the equation proposed by V. M. Eroshenko and L. A. Yaskin [4], the heat transfer is affected mostly by change in specific heat.

All theoretical and experimental studies of heat transfer under supercritical pressures known to these authors cover only the near-critical range of temperature variation in the liquid ($T_L/T_w > 0.9$). This can be explained by the fact that in existing structures of supercritical-pressure steam boilers the feed water enters the boiler already preheated to a near-critical temperature. With further boosting of the thermal intensity levels in supercritical-pressure power plants, however, it is feasible to build structures where heat transfer in the liquid will occur with the latter appreciably underheated to a pseudocritical temperature. It is of considerable interest to know how the laws of heat transfer will change under these conditions.

In this report experimental data are presented on heat transfer to various liquid hydrocarbons over a wide range of their temperature, namely from 0.4 T_L/T_m to 1.0 T_L/T_m. Test results pertaining to heat transfer to kerosene are shown in Fig. 2 in the form of $\alpha/\alpha_0 = f(T_w/T_m)$ curves for various values of T_L/T_m. The wide spread of values (shaded area between curves) is attributable to the range of variation of process parameters, their role not being fully taken into account in the given method of data generalization, and also to solid deposits forming during heat transfer to liquid hydrocarbons, making measurements of the true temperature of the cooled surface difficult. All experiments were performed with pipes 3 mm in diameter.

According to the results of these experiments, heat transfer to kerosene at a temperature T_L close to T_m (Fig. 2a) becomes weaker as temperature T_w rises, which agrees completely with the aforementioned theoretical and empirical relations. At a lower kerosene temperature ($T_L/T_m = 0.8$) the heat transfer did not weaken so much with rising wall temperature T_w/T_m (Fig. 2b), and at still lower kerosene temperatures ($T_L/T_m = 0.58$–0.4) a rise of temperature T_w caused not an attenuation, but an intensification of heat transfer (Figs. 2c, d).

The same results were obtained in experiments with diisopropyl cyclohexane [8], ethanol [9], and n-heptane [10]. The corresponding $\alpha/\alpha_0 = f(T_w/T_m)$ curves are shown in Fig. 3.

Evidently, a change in the temperature of the liquid, or, more correctly, a change in the level of underheat below T_m in a turbulent stream under supercritical pressure, causes a qualitative change in the mode of heat transfer: a rise of the wall temperature T_w, causing attenuation of the heat transfer when the underheat is small, and causing an intensification of heat transfer when the underheat is large. In this author's view, the intensification of heat transfer in the case of large underheat below T_m and high wall temperature (large overheat of wall above T_m) is caused by breakdown of the gaseous boundary layer and occurrence of so-called pseudoboiling. The process of heat transfer with pseudoboiling has been described in many studies [6]. In terms of its characteristics it is analogous to the process of heat transfer with surface (underheated) boiling. On photographs "pseudobubbles" appear just as vapor bubbles [11]. From this author's study of heat transfer with pseudoboiling, made by means of high-speed photography in an annular channel with transparent outer wall, it has been possible to deduce the following concept about the mechanism of this process [12]: When $T_L \ll T_m$ and $T_w \gg T_m$, i.e., when the core of the turbulent stream in a pipe contains cold liquid and the boundary layer contains hot gas, then turbulent vortices

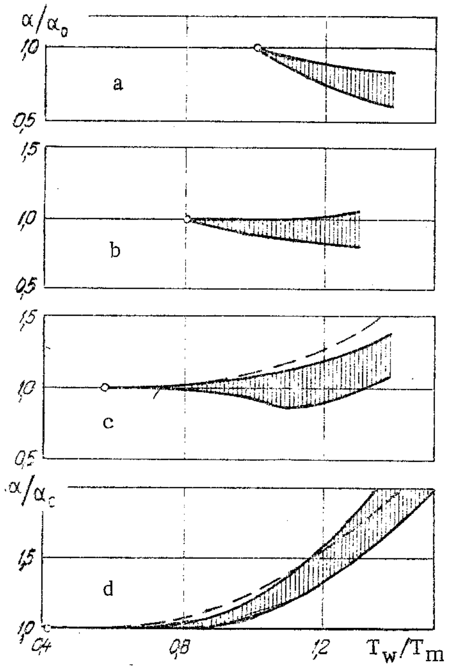

Fig. 2

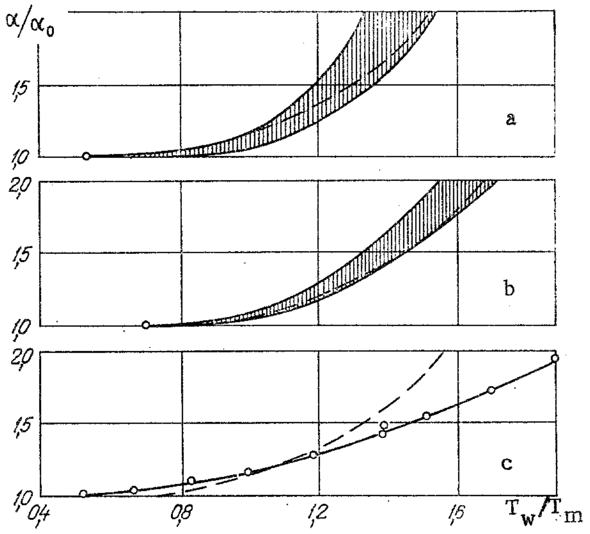

Fig. 3

Fig. 2. Dependence of α/α_0 on T_w/T_m during heat transfer to kerosene (T_{cr} = 673°K, p_{cr} = 20 bar): a) T_L/T_m = 0.95-1.0, p = 20-100 bar, $w\rho = 2\cdot10^3$ kg/(m²•sec); b) T_L/T_m = 0.79-0.81, p = 100 bar, $w\rho = 10\cdot10^3$ kg/(m²•sec); c) T_L/T_m 0.56-0.58, p = 100 bar, $w\rho = 30\cdot10^3$ kg/(m²•sec); d) T_L/T_m = 0.40-0.42, p = 40-100 bar, $w\rho = 10\cdot10^3-20\cdot10^3$ kg/(m²•sec).

Fig. 3. Dependence of α/α_0 on T_w/T_m during heat transfer to diisopropyl cyclohexane (T_{cr} = 650°K, p_{cr} = 25 bar, T_L/T_m = 0.54, p = 45 bar, w = 2-15 m/sec, d = 1.6 mm); b) ethanol (T_{cr} = 516°K, p_{cr} = 65 bar, T_L/T_m = 0.7, p = 300 bar, w = 6.5-20 m/sec, d = 2.1 mm); c) n-heptane (T_{cr} = 540°K, p_{cr} = 27 bar, T_L/T_m = 0.52, p = 40 bar, $w\rho$ = 2500 kg/(m²•sec); annular channel 3/4 mm.

break up the gaseous boundary layer and throw separate fragments of it into the cold stream core. There surface tension produced by the large difference of densities shapes these fragments into bubbles ("pseudobubbles"). Rapid cooling and compression of these bubbles result in additional turbulization, which intensifies the heat transfer. The reverse process, separate fragments of cold liquid falling from the stream core onto the hot wall, results in formation of "drops", and rapid heating with expansion of the latter also causes additional turbulization. Compression and expansion of pseudobubbles will generate thermoacoustic vibrations, but that phenomenon is not a subject of this study.

We must dwell briefly on the subject of surface tension under supercritical pressures. It is well known that the surface tension between a liquid and its vapor decreases with rising pressure as the difference between the densities of liquid and vapor decreases. This applies, however, only to a liquid-vapor system at thermodynamic equilibrium. When the substance under supercritical pressure is not at thermodynamic equilibrium and includes separate regions with different temperatures and densities, then between these regions there can appear a surface tension of a magnitude which is given approximately by the Bachinskii relation $\sigma = c(\rho_1 - \rho_2)^4$.

The surface tension will tend to contract the surface between volumes of liquid with different densities and thus to shape it into a spherical one. According to the Laplace equation, the pressure Δp which compresses the volumes of liquids with lower density is higher when these volumes are smaller:

$$\Delta p = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right).$$

Since the dimensions of turbulent vortices are smaller in a pipe with a smaller diameter, the surface tension will also exert a stronger force on the turbulent structure in a pipe with a smaller diameter. It is to be recalled here that a real interface at which surface tension forces act constitutes a zone of finite width, within which the density of the substance gradually changes.

It is obvious that heat transfer with pseudoboiling cannot be described by the laws of plain convective heat transfer, even when variation of the properties of the liquid over the stream cross section has been taken into account. (Just as heat transfer with surface boiling under subcritical pressures cannot be described by these laws).

It is not feasible at this time to obtain a more-or-less accurate relation describing the laws of heat transfer with pseudoboiling. Only an empirical one can be proposed for an approximate generalization of the experimental data in Figs. 2 and 3, namely:

$$\alpha/\alpha_0 = 1 + \left(\frac{T_W - T_L}{T_m}\right)^{2,33}.$$

The dependence of the heat transfer coefficient on the temperature difference $(T_W - T_L)^{2.33}$ is characteristic of the pseudoboiling process as well as of boiling proper. This relation is valid for T_L/T_m from 0.4 to 0.8 and T_W/T_m from 1.0 to 1.5. Results of calculations according to this relation are shown in Figs. 2 and 3 with dashed lines.

NOTATION

d, pipe diameter; p, pressure; p_{cr}, critical pressure; T_L, mean-mass temperature of the liquid; T_W, wall temperature; T_m, pseudocritical temperature of phase transformation under supercritical pressures (temperature corresponding to maxima of specific heat); R_1 and R_2, principal radii of a volume; $w\rho$, mass rate of fluid flow; α, heat transfer coefficient; α_0, heat transfer coefficient at a temperature T_W close to T_L; ρ_L, density of the liquid at the mean-mass temperature; ρ_W, density of the liquid at the wall temperature.

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