HEAT TRANSFER TO ASCENDING AND DESCENDING TURBULENT STREAMS OF AROMATIC HYDROCARBONS AT NEAR-CRITICAL PRESSURES

A. M. Mamedov, F. I. Kalbaliev, and G. I. Isaev UDC 536.24

The character of the distribution of wall temperature along the length of the tube is given. It is established that on the basis of the $t_w = f(q)$ graph the trend of the temperature curve changes several times but twice in certain sections it is accompanied by an improvement in heat transfer.

The process of heat transfer to a liquid near its critical pressure has unusual characteristics if its temperature is lower and the wall temperature is higher than the pseudocritical temperature (t_m). Numerous reports have been devoted to the study of this phenomenon. The results of experimental studies of the heat transfer show that in a number of cases the heat transfer is accompanied by oscillations in the pressure (sound) and wall temperature [1-3, 7]. Normal [5], improved [1], and impaired [4] modes of heat transfer at supercritical pressure have been observed in the works of individual investigators. The study of these phenomena requires further experimental investigations of the heat transfer of different liquids with $p > p_{cr}$.

Some results of an experimental investigation of heat transfer to ascending and descending turbulent streams of aromatic hydrocarbons with $t_l < t_m \gtrless t_w$ and near-critical pressures $(1 < p/p_{cr} < 1.25)$ are presented in the present report.

As the heat-transfer agents we chose (the aromatic hydrocarbons) toluene and benzene, which have the following critical parameters: $p_{cr} = 42.358$ bars and $t_{cr} = 320.8°C$ for toluene and $p_{cr} = 49.4$ bars and $t_{cr} = 289°C$ for benzene.

The tests were conducted on an installation which consisted of an open circulation loop. The experimental section was a tube of 1Kh18N10T stainless steel with an inner diameter $d_i = 2.10$ mm, thickness $\delta = 0.46$ mm, and length $l = 170$ mm which was heated by an alternating electric current of low voltage.

The tests were performed in the following order. The required power was supplied to the experimental tube with constant pressure, flow rate, and temperature of the liquid at the inlet. The heat flux remained constant and was changed only in going from one test to another. In performing the experiments the pressure and temperature of the liquid at the inlet and outlet, the current strength, and the voltage drop on the experimental tube were measured. The wall temperature was measured with six thermocouples along the length of the tube. The temperature at the inner surface of the tube was determined by calculation. All the thermocouples were made of Chromel–Alumel wire 0.2 mm in diameter.

The temperature pulsations were recorded with an ÉPP-09 recording instrument of accuracy class 0.5, while the pressure pulsations were measured at the exit from the tube with primary and secondary instruments of accuracy class 1 (an automatic recording instrument with a DSR1-01 differential-transformer circuit and an MÉD manometer).

Typical graphs of the variation in wall temperature along the length of the tube with ascending and descending streams of toluene are shown in Fig. 1, from which it is seen that when the wall temperature is less than the pseudocritical temperature ($t_m = 336°C$) the nature of the variation in wall temperature along the length of the tube is the same in both cases as with ordinary convective heat exchange (curve 1). As the wall temperature approached t_m of the liquid in the experimental tube a loud sound appeared, like a whistle. With

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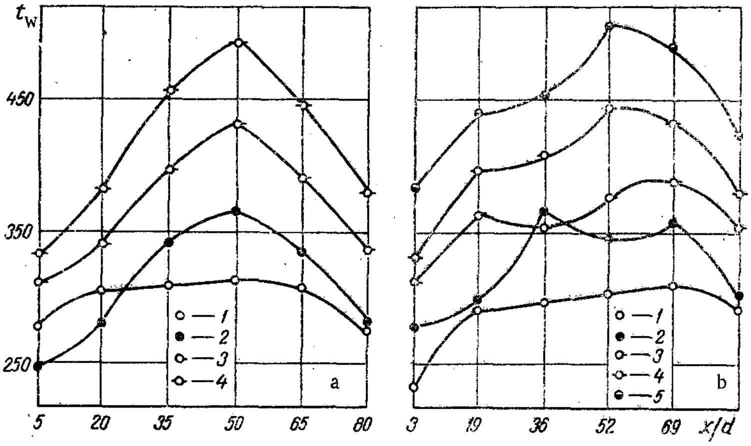

Fig. 1. Distribution of wall temperature along length of tube, $p = 50$ bars: a) ascending stream, $\rho w = 3168$ kg/m^2 · sec, $t_l^{in} = 15°C$, $Re = (11\text{-}53) \cdot 10^3$; 1) $q \approx 1.8 \cdot 10^6$; 2) $3.15 \cdot 10^6$; 3) $4.0 \cdot 10^6$; 4) $q \approx 4.85 \cdot 10^6$ W/m^2; b) descending stream, $\rho w = 3183$ kg/m^2 · sec, $t_l^{in} = 25°C$, $Re = (11\text{-}40) \cdot 10^3$; 1) $q \approx 1.7 \cdot 10^6$; 2) $3.16 \cdot 10^6$; $3.48 \cdot 10^6$; 4) $4.25 \cdot 10^6$; 5) $q \approx 5.06 \cdot 10^6$ W/m^2.

an increase in the heat flux the wall temperature slowly increases and in some section along the length of the tube (usually above the midsection) a value approximately equal to t_m is reached. With a further increase in the heat flux the wall temperature in this section grows with the appearance of maxima. It should be noted that with $p = 50$ bars and an ascending stream there is one wall temperature maximum along the length of the tube, which is usually observed at $x/d \approx 50$ from the tube inlet. With a descending stream the temperature distribution along the length of the tube seems at first to have two maxima (curves 2 and 3 in Fig. 1b), but with an increase in the heat flux density the nature of the wall temperature distribution changes somewhat and one maximum with a weakly expressed character remains. In these tests the wall temperature increases strongly in the initial section of the tube ($x/d \lesssim 20$), then ($20 \lesssim x/d \lesssim 52$) its smooth growth is observed, and it decreases in the last section of the tube (curves 4 and 5 of Fig. 1b).

The dependence of the wall temperature on the heat flux density with about the same temperature and flow velocity of the liquid at the tube inlet for ascending and descending toluene streams of $Re = 11 \cdot 10^3$ and $Re = 12 \cdot 10^3$, respectively, and for benzene with ascending movement but lower flow velocities of $Re = 8.5 \cdot 10^3$ is presented in Fig. 2.

These graphs were plotted for the thermocouple located at a distance $x/d \approx 50\text{-}52$ from the entrance. It is seen from the figure that the curves have the same character and represent a complex dependence $t_w = f(q)$ on the whole. In section AB with $t_w < t_m$ the graphs have a straight character, i.e., like that for ordinary convective heat exchange. After point B the wall temperature grows slowly with an increase in the heat flux density. For example, in the tests with toluene with $p = 50$ bars, $t_l^{in} = 15°C$, and $\rho w = 3168$ kg/m^2 · sec, an increase in the heat flux from $q \approx 1.6 \cdot 10^6$ W/m^2 to $q \approx 3.0 \cdot 10^6$ W/m^2 (from point B to point C) led to an increase of about 40°C in the temperature (from 300 to 340°C). It is seen from a comparison of sections AB and BC of the curve that in section AB the wall temperature grows to about 300°C with an increase in the heat flux to $q \approx 1.5 \cdot 10^6$ W/m^2. Evidently, after point B the temperature in the near-wall layer approaches the pseudocritical temperature of the test liquid. When this happens the thermophysical properties of the liquid change strongly (c_p reaches its maximum), which also promotes an improvement in heat transfer. At the end of this section (at point C) the wall temperature reaches approximately the pseudocritical temperature.

With constant values of t_l^{in} and ρw the slope of curve BC depends on the pressure. With an increase in the latter the slope of the curve in this section increases. In a majority of the tests some decrease in the wall temperature is observed at the end of section BC with an increase in the heat flux. This is explained by a sharp increase in the heat capacity c_p at a near-pseudocritical temperature. After the wall temperature reaches a value equal to t_m of the liquid, the wall temperature grows with an increase in the heat flux density and section CD is obtained, which is somewhat like section AB in character and differs only in the slope.

With larger heat flux densities and high wall temperatures the trend of the temperature curve changes

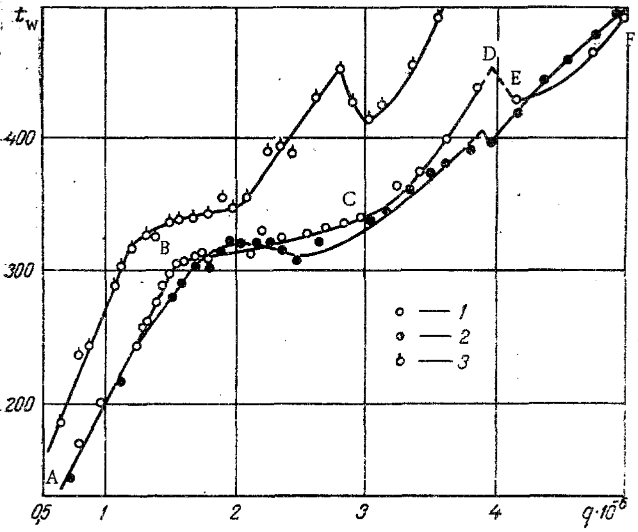

Fig. 2. Dependence of wall temperature on heat flux density: 1) toluene, ascending stream, p = 50 bars, $\rho w = 3168\ kg/m^2 \cdot sec$, $t_l^{in} = 15°C$; 2) toluene, descending stream, p = 50 bars, $\rho w = 3183\ kg/m^2 \cdot sec$, $t_l^{in} = 25°C$; 3) benzene, ascending stream, p = 60 bars, $\rho w = 2521\ kg/m^2 \cdot sec$, $t_l^{in} = 22.5°C$.

once again and section DEF is obtained. In this section the graph of wall temperature at first decreases from the value corresponding to point D to the value of E with an increase in the heat flux and then (after E) grows relatively slowly with an increase in the heat flux density. In some tests the decrease in the wall temperature from the value of D to that of E is slight and section DEF on the graph of $t_w = f(q)$ can be joined by a smooth curve. The character of the variation in the $t_w = f(q)$ curve depends on the mode of flow, particularly on the Reynolds number. Curves of the dependence $t_w = f(q)$ for laminar and turbulent modes of flow with $p > p_{cr}$ and their comparison are given in [9].

On the basis of the plotted graph one can conclude that the curve of the dependence $t_w = f(q)$ changes several times (sections BC and DEF) and the heat transfer improves twice. The initial improvement can be explained by a strong change in the thermophysical properties of the liquid, but the second change in the trend of the temperature curve does not yield to a precise explanation. It is possible that the test liquid breaks down at high temperatures and large heat fluxes, forming gases which intensify heat transfer. However, additional studies with other liquids under different conditions are required for a decisive explanation of this phenomenon.

The indicated form of the dependence of t_w on q was not observed in the work of other investigators with turbulent flow and $p > p_{cr}$. This pertains especially to the second change in the wall temperature (section DEF) on the graph of $t_w = f(q)$. There are some helpful data relative to this section of the curve in the literature, however. For example, Kafengauz [1] in tests with diisopropyl cyclohexane with $p > p_{cr}$, w = 6 m/sec, and $t_w > t_m$ observed first a decrease in the wall temperature and then its gradual growth with an increase in q. The same form of the dependence of t_w on q is described in [3] by Kaplan and Tolchinskaya in tests with n-heptane with a velocity w = 10 m/sec, $t_l^{in} = 20°C$, and p = 40 bars. The graph of $t_w = f(q)$ plotted in [1, 3] show that for these liquids t_w first grows with an increase in q as in ordinary convective heat exchange and then when $t_w > t_m$ the wall temperature falls by several degrees and goes on to grow slowly as q increases. Test data obtained with free movement of the liquid in [8] and [6] indicate the possibility of obtaining the section DEF on the curve of $t_w = f(q)$ for carbon dioxide. The authors of these reports corroborate the existence of bubble flow (pseudoboiling) with carbon dioxide at supercritical pressure.

We note that in the tests the section BCDEF shown in Fig. 2 was accompanied by sounds of different tones, the appearance of which corresponds to point B on the curve of $t_w = f(q)$. At first, they had a periodic character, i.e., now appearing now disappearing, but as the heat flux increased the tone of the sound became constant and stronger. However, this phenomenon depends on the value of Re, since the strength of the sound decreases with a decrease in the latter [9]. The sound oscillations are accompanied by oscillation in the wall

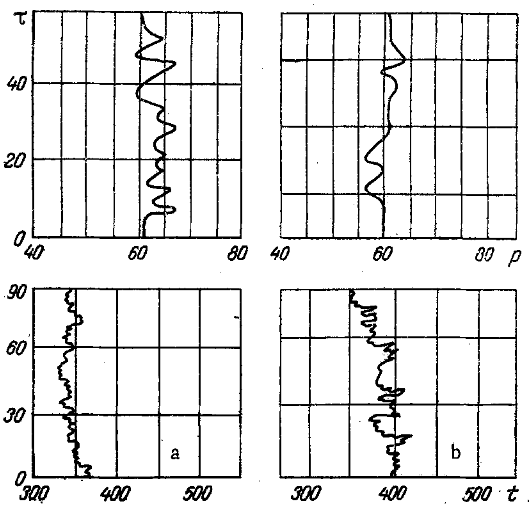

Fig. 3. Graphs of pressure and temperature oscillations. Benzene, p = 60 bars, $\rho w = 2521\ kg/m^2 \cdot sec$, $t_l^{in} = 22.5°C$, Re = $(8.5\text{–}40) \cdot 10^3$.

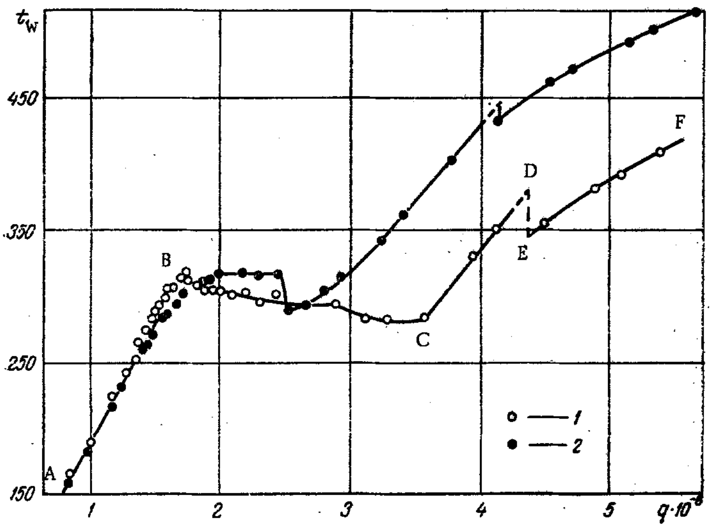

Fig. 4. Dependence of wall temperature on heat flux density for thermocouples located at different distances from tube inlet; p = 45 bars, $\rho w = 3168\ kg/m^2 \cdot sec$, $t_l^{in} = 20°C$, Re = $(11\text{–}48) \cdot 10^3$; 1) x/d = 20; 2) x/d = 50.

temperature (Fig. 3). Graphs of the pressure oscillation, measured in tests with p = 60 bars and an ascending benzene stream, are also presented in Fig. 3. Figure 3a corresponds to section BC, while Fig. 3b corresponds to section CD of the curve of $t_w = f(q)$. It is seen from the figures that the pressure oscillation reaches 7 bars while the temperature oscillation comprises 15°C for the most part. In some cases sharp pressure oscillations were accompanied by sharp oscillations in the wall temperature. In section DEF the tone of the sound decreased from a loud whistle to a soft hiss, with the size of the pulsations in wall temperature decreasing.

Graphs of the dependence $t_w = f(q)$ at near-critical pressure ($p/p_{cr} = 1.07$) for an ascending toluene stream are presented in Fig. 4. These graphs were constructed from the readings of two thermocouples located at different distances from the tube inlet (x/d = 20, 50), from which it is seen that the curves have a common nature of variation but their individual sections differ from one another. For example, the sections BC have different lengths and sections CDEF differ in the value of the wall temperature at the same heat fluxes. Thus, for the initial section of the tube the sections CDEF are shifted to the right, i.e., towards larger values of q.

Thus, maxima in the wall temperature and, accordingly, minima in the heat-transfer coefficient are observed in several sections of the tube on the graphs of $t_w = f(x/d)$ (Fig. 1a, b). The graphs of the dependence $t_w = f(q)$ show that the maxima in wall temperature along the length correspond to sections CD (Fig. 2). It follows from Fig. 1a, b that a maximum in the wall temperature is not observed in the readings of all the thermocouples located at different distances along the length of the tube. But the graph of $t_w = f(q)$ constructed for thermocouples located at different distances from the tube inlet (Fig. 4) shows that the sections CD where t_w grows with an increase in q are obtained for all the thermocouples.

Consequently, it is probably more advisable to judge the mode of heat transfer not from the graph of $t_w = f(x/d)$, but from the dependence $t_w = f(q)$.

NOTATION

t_w, t_l, temperatures of wall and liquid, °C; t_l^{in}, liquid temperature at tube inlet, °C; p, pressure, bars; t_{cr}, critical temperature, °C; p_{cr}, critical pressure, bars; q, heat flux density, W/m^2; ρw, mass flow rate, $kg/m^2 \cdot sec$; τ, time, sec; t_m, pseudocritical temperature.

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SELECTION OF SIMILARITY CRITERIA IN STUDYING THE EFFECT OF ROTATION ON HEAT EXCHANGE IN TURBINE BLADES

V. A. Trushin

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The supplementary factors affecting the nature of the flow and heat exchange in rotating turbine arrays and the supplementary criteria reflecting the effect of rotation on heat exchange in turbine blades on the gas and air sides are discussed.

By now rather extensive experimental data have been accumulated on the intensity of heat exchange between a gas and rotating turbine blades [1-7]. In [1, 3] the experimental results are given without generalization, but it clearly follows from them that rotation not only considerably intensifies but also causes a redistribution of the heat-exchange coefficient over the contour of the profile in a rotor array. In [2] the experiments are generalized for conditions of nonisothermal flow in the interblade channels, while in [4, 5] they are generalized for cases which are close to isothermal. In [6, 7] the heat exchange was estimated by an indirect method based on measurements of the blade temperatures with subsequent inverse calculation. The effect of

S. Ordzhonikidze Ufa Aviation Institute.

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