HEAT-TRANSFER MECHANISM IN TURBULENT FLOW OF FLUID AT SUPERCRITICAL PRESSURES

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UDC 536.242:532.517.4

A hypothetical physical model of the heat-transfer process accompanying a forced flow of liquid at supercritical pressures is proposed. This model accounts for the anomalous improvements and deteriorations in heat transfer which are characteristic of this region.

Heat-transfer conditions associated with a turbulent flow of liquid at supercritical pressures are encountered in several areas of modern technology. The supercritical region is characterized by anomalous variations in heat transfer – in some cases there is an improvement in heat transfer [1-5], while in others there is deterioration [6, 7]. Various investigators have attempted to devise methods of calculating the heat transfer [8-12]. These methods, however, lead to good agreement with experiments for some conditions, but are unsatisfactory for others.

For instance, the intensification of the heat transfer observed in the investigation of water [1] cannot be calculated by the theoretical methods of [8, 9, 11, 12], which take into account the effect of the variable thermophysical properties of the liquid on the velocity and temperature profiles in forced-convection conditions. This indicates that the physical model of the process has not been adequately considered.

Goldmann [9] in a discussion of Deissler's paper introduced the concept of "pseudoboiling" to account for the anomalous improvement in heat transfer. Goldmann pictures clusters of liquid molecules as bursting, on coming into contact with the heat-transfer surface, into pockets of gaslike (single) molecules within the liquid. The growth and subsequent collapse of these pockets resembles nucleate boiling.

Hines and Wolf observed pressure oscillations and an improvement in heat transfer at wall temperatures exceeding the critical temperature, whereas Griffith and Sabersky [14] found no improvement in heat transfer in the case of natural convection of Freon 114A at supercritical pressures, although they observed the movement of bubble-like formations in the experiments. In view of this inconsistency Hines and Wolf suggested that there is some mechanism other than Goldmann's density bubbles. They put forward their own hypothesis regarding the mechanism responsible for the pressure oscillations and improvement in heat transfer in forced flow of liquid at supercritical pressures.

In view of the rapid change in viscosity with temperature near the critical point they suggest that a random small increase in wall temperature causes an appreciable reduction of the thickness of the laminar boundary layer. This reduction in thickness of the boundary layer will lead to a drop in wall temperature and a corresponding increase in viscosity, which will result again in an increase in thickness of the laminar boundary layer. This will result again in an increase in wall temperature and the cycle will be repeated. The authors think that such an unstable boundary layer may be responsible for the oscillations at supercritical pressures and the increase in heat transfer in a forced-convection system.

It was shown experimentally in [4, 5] that, when the wall temperatures reach values close to T_m, high-frequency pressure oscillations arise in the system, but these do not lead to an improvement in heat transfer in every case.

That the presence of high-frequency pressure oscillations accompanying forced convection does not lead to an improvement in heat transfer indicates that the heat-transfer mechanism proposed by Hines and Wolf does not satisfactorily represent the physical model of heat transfer at supercritical pressures.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 21, No. 3, pp. 431-437, September, 1971. Original article submitted October 9, 1970.

We note that the discussed hypotheses fail to account for the deterioration in heat transfer observed in the supercritical region.

Below we attempt to construct a physical model of heat transfer in a turbulent flow of liquid which will account simultaneously for the observed anomalous improvement and deterioration of heat transfer in the region of supercritical state variables.

In the general case of heating of a liquid in the region of near-critical parameters we can distinguish four main cases of heat transfer according to the temperatures of the wall and liquid:

1) $T_W \gg T_m$, $T_L \ll T_m$;

2) $T_W \gg T_m$, $T_L = T_m$ or slightly less than T_m;

3) $T_W \gg T_m$, $T_L > T_m$;

4) T_W a little greater than T_m, T_L a little less than T_m.

As Krasnoshchevskii and Protopopov [6] showed, heat transfer at relatively low temperature heads ($T_W \leq 1.1\ T_m$, case 4), and also at high temperature heads (~400°C) and liquid temperatures above T_m (case 3) is satisfactorily predicted by the formula proposed by Petukhov and Kirillov for convective heat transfer [19]:

$$\mathrm{Nu}_0 = \frac{\xi/8\ \mathrm{Re}\,\mathrm{Pr}}{12.7\sqrt{\xi/8}\,(\mathrm{Pr}^{2/3} - 1) + 1.07}, \qquad (1)$$

$$\xi = (1.82\ \lg \mathrm{Re} - 1.64)^{-2}.$$

Thus, it is only in cases 1 and 2 that there are anomalous deviations of the heat transfer from the convective value.

In the first case of heat transfer ($T_W \gg T_m$; $T_L \ll T_m$) at moderate flow velocities (say 6-15 m/sec) there is a pronounced intensification of heat transfer with increase in heat flux.

Figure 1 shows a typical relationship $T_W = f(q)$ obtained in such experiments with n-heptane [4]. Similar relationships have been obtained for diisopropylcyclohexane [2], ethyl alcohol [3], and other liquids. The pressure in these experiments was above the critical value, but less than $P/P_{cr} = 5$.

The following characteristic features of the considered case of heat transfer should be noted.

At low positive values of the difference ($T_W - T_m$) high-frequency pressure oscillations were observed. The heat transfer in this case showed no change with increase in wall temperature up to 500°C. A further increase in heat flux led to an improvement in heat transfer.

At heat fluxes corresponding to the pronounced change in heat transfer rate the wall temperature periodically fell and increased again.

The temperature corresponding to the "platform" on the curve of $T_W = f(q)$ (Fig. 1) was higher than T_m.

An increase in flow velocity with the pressure constant leads to a reduction of the wall temperature at which the heat transfer becomes more intense [2, 4].

From these experimental features we can make the following inferences.

1. The transition to improved heat transfer is a typical crisis effect.
2. In the case of onset of improved heat transfer the flow becomes turbulent only in the region bounded by the section with temperature T_m, and not throughout the boundary layer (right up to the heat-transfer surface), as Goldman [9] suggested.

In fact, at wall temperatures higher than T_m a layer of substance with supercritical parameters is formed at the heat-transfer surface. Spectroscopic and x-ray investigations have shown that in the supercritical region the state diagram of the substance consists of two different parts separated by a curve which is a continuation of the liquid–vapor equilibrium line. When this curve is crossed the structure of the substance changes, exhibiting the properties of a liquid or gas [16]. The structure of the substance on this line is unstable [17].

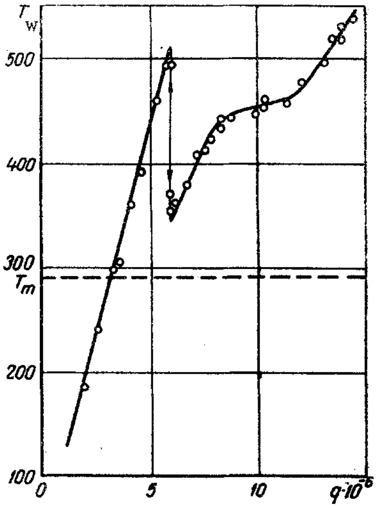

Fig. 1

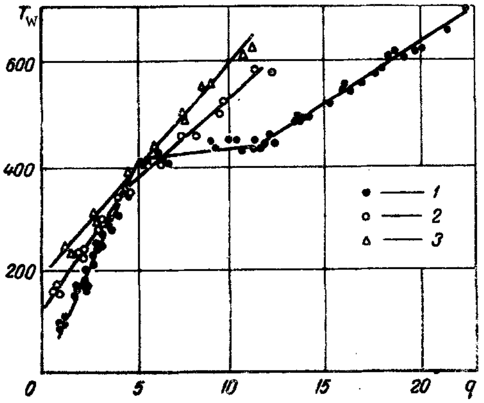

Fig. 2

Fig. 1. Heat transfer in forced flow of n-heptane (T_L = 20°C, d_{int}/d_{ext} = 2.02/2.52 mm, l = 40 mm, w = 10 m/sec, P/P_{cr} = 1.45). T_w, °C; q, W/m^2.

Fig. 2. Heat transfer in case of forced flow of light oil in annular channel (d_{ext}/d_{int} = 3/2 mm, P/P_{cr} = 2, w = 15 m/sec, l/d_e = 40): 1) T_L = 30°C; 2) 100; 3) 200. T_w, °C; q, W/m^2.

It is obvious that the pressure oscillations which arise in the system when the wall temperature passes through the value T_m are due to structural changes in the medium which gradually take place in the temperature region close to T_m.

The production of pressure oscillations in the boundary layer region with temperature close to T_m will obviously lead to some reduction of its retarding effect on the layer with lower temperature, and this will result in an increase in velocity of the layer with temperature ($T_m - \Delta T$). In turn, owing to reduction of the accelerating effect of the layer with temperature ($T_m - \Delta T$) on the layer with temperature ($T_m + \Delta T$) there will be a reduction of the velocity of the layer with temperature ($T_m + \Delta T$) in comparison with its velocity prior to alteration of the velocity field. The reduction of the velocity of the layer with temperature ($T_m + \Delta T$) will lead to an increase in thickness of the gaseous sublayer with temperature between T_m and T_w.

An increase in thickness of the gaseous sublayer can also be expected from the following considerations. If an increase in the velocity of the layer with temperature ($T_m - \Delta T$) occurs, it will be compensated by a reduction in velocity and increase in thickness of the gaseous sublayer, since the liquid flow rate, like the cross section of the tube, does not vary with length.

Thus, the onset of the crisis leads, on one hand, to an increase in thermal resistance of the gaseous sublayer and, on the other, to an intensification of heat transfer due to an increase in molar transfer. In the case where $T_L \ll T_m$ the increase in heat transfer due to the increase in molar transfer is greater than the deterioration of heat transfer due to the increase in thermal resistance of the gaseous sublayer and the resultant effect is an improvement in heat transfer.

When $T_w \gg T_m$, and T_L is a little less than T_m (case 2), the increase in thermal resistance of the gaseous sublayer is the decisive factor and there is a deterioration of heat transfer.

The proposed heat-transfer mechanism is consistent with all the experimental data known to us. For instance, according to the postulated mechanism we would expect the greatest deterioration in heat transfer with $T_L \approx T_m$ and high wall temperatures. In fact, in these conditions the coefficient of heat transfer to carbon dioxide is reduced by a factor of 14 [6] in comparison with the value calculated from Eq. (1).

Furthermore, if the greatest deterioration in heat transfer occurs when $T_L \approx T_m$, and heat transfer is improved when $T_L \ll T_m$, we can predict that at intermediate liquid temperatures we will have conditions in which there will be no improvement in heat transfer in comparison with the convective region.

We did, in fact, observe a reduction in heat transfer with increase in liquid temperature at the entrance to the working section (Fig. 2). An increase in liquid temperature at the entrance from 30 to 100°C led to a deterioration in heat transfer. With further increase in liquid temperature to 200°C there was no change in heat transfer in comparison with the convective region.

We must infer that the instability of the boundary layer, which leads to a change in the nature of the heat transfer, is due not only to the change in the structure of the medium on passage through T_m and the concomitant high-frequency pressure oscillations, but obviously also depends on the external turbulent disturbances penetrating into the boundary layer from the stream core. Hence, at low flow rates the intensification of the heat transfer occurs at higher wall temperatures, i.e., when the layer with temperature T_m is at some distance from the wall. For the same reason the experimental data relating to cases where the boundary layer has passed through T_m, but the wall temperature is insignificantly greater than T_m (case 4) and the flow velocity is low [18], are predicted by the relationship for convective heat transfer in a single-phase medium with variable physical properties [13].

It should be noted that the proposed physical model of the heat-transfer mechanism in a forced flow of liquid at supercritical pressures applies only to a certain range of parameters. Although we do not have sufficient experimental data at present for a reasonably accurate demarcation of the region in which the given mechanism operates, we can nevertheless obtain a rough idea. These heat-transfer features will be exhibited in a certain range of pressures (obviously $1 < P/P_{cr} < 6$) and mass flow rates (w = 5-15 m/sec, say $10^{-4} < \mathrm{Re} < 8 \cdot 10^4$). A characteristic feature of this region is that an increase in Re leads to a reduction of the wall temperature at which heat transfer begins to improve (Fig. 2 [2]). With increase in flow velocity the wall temperature at which heat transfer begins to improve is reduced and in these conditions the heat-transfer mechanism obviously acquires the characteristic features in [4].

The postulated mechanism of heat transfer in a forced flow of liquid is also consistent with the experimental relationships obtained in the case of cooling of a medium at supercritical pressure with $T_L > T_m$ and $T_W < T_m$. In this case the wall is in contact with a liquid phase the thermal resistance of which is much lower than that of the gaseous phase. Hence, in the case of alteration of the velocity field the intensification of heat transfer is due not only to an increase in molar transfer, but also to a significant reduction in thermal resistance of the boundary layer, since there is an increase in turbulence in the part of the boundary layer composed of gas. The increase in thickness of the liquid sublayer must obviously affect the total thermal resistance of the boundary layer. Hence, in the case of cooling of a medium we will not observe the reduction in heat transfer which occurs in the case of heating.

In fact, in the case of cooling of carbon dioxide at supercritical pressure the heat-transfer rate is several times higher than that calculated from Eq. (1). The greater the temperature head, other conditions being equal, the greater the intensification of heat transfer [20].

An improvement in heat transfer is also observed in the case of cooling of water in the near-critical region [21].

Thus, the presented hypothesis accounts for the anomalous deviations in heat transfer in different conditions, which indicates that it represents fairly correctly the physics of the processes associated with heat transfer at supercritical pressures.

NOTATION

T_L	is the liquid temperature;
T_W	is the wall temperature;
T_m	is the temperature of maximum heat capacity;
q	is the heat flux;
Nu_0	is the Nusselt number determined from Eq. (1) at temperature T_L;
w	is the flow velocity;
P	is the pressure in the working section;
P_{cr}	is the critical pressure;
d	is the tube diameter;
l	is the length of the heated section.

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