# HEAT EXCHANGE DURING THE FORCED FLOW OF HYDROCARBON FUELS AT SUPERCRITICAL PRESSURES IN HEATED TUBES

L. S. Yanovskii and B. Ya. Kamenetskii

UDC 536.24

*Heat transfer coefficients have been measured during the turbulent flow of hydrocarbon fuels at supercritical pressures under conditions in which no deposits occur. It is shown that a regime of impaired heat exchange can occur when the stream and wall temperature values are lower than the pseudocritical temperature of the fuel. The boundaries of this regime are established and empirical relationships are proposed for calculating the impaired and normal heat exchange.*

Turbulent heat exchange during the forced flow in channels of liquid hydrocarbons at supercritical pressures (SCP) is characterized by certain anomalies, and in particular by a considerable impairment of heat transfer in certain regimes. The local overheating of the walls (temperature peaks) which occur in this case facilitate the formation of carbonaceous deposits of low thermal conductivity which lead to disruptions in the normal operation of energy equipment [1]. As is well known [2], the sharp reduction in turbulent heat exchange in the viscous-inertial regime of flow at SCP is connected with changes in the thermophysical properties of the material over the cross section and length of the stream which are very considerable in the pericritical zone, when the pseudocritical temperature falls between the values of the mass-average temperature of the stream and the temperature of the surface ($t_f < t_m < t_w$). The impaired heat exchange occurring under the same conditions in the viscous-inertial regime of flow at SCP for liquid hydrocarbons with broad distillation curves has not been sufficiently studied in the past: the great bulk of investigations have been carried out mostly for individual (aromatic and saturated) hydrocarbons ([3], for example), and only a small amount of other work carried out for kerosenes is known ([4], for example). These investigations were carried out in short tubes ($l$ = 0.06 m; $l/d$ = 30), and the analysis of the heat exchange was based on measurements of the wall temperatures at one cross section of the tube, and did not take into account the effects of carbonaceous deposits. Even the possibility of using existing heat transfer models based on experimental data obtained for individual materials for hydrocarbons with broad distillation curves requires experimental configuration.

The present paper presents the results of investigations of the heat exchange behavior of various hydrocarbon fuels at SCP in long horizontal tubes of small diameter. The experiments were carried out in an open-circuit flow unit with a working section heated by an ac electrical current. As the working section, use was made of replaceable tubes (from one batch) of 12Kh18N9T (12Cr18Ni9Ti) stainless steel of length 1 m and inside diameter 0.001 m. The equipment and the measurement procedures have been described in [5].

The standard fuel oils RT (GOST 10227-86) and T-6 (GOST 12308-80) were selected as the test materials; these oils differ considerably from one another in their physical—chemical properties. The fuel was first deoxygenated, and after each test (of duration 2-3 minutes), the tube was replaced by a new tube, which, as indicated by control tests, made it possible to practically eliminate the effect of carbonaceous deposits on heat exchange.

The experiments were carried out for the following ranges of the main parameters:

| | |
|---|---|
| pressure at the inlet of the working section: | 3.0 and 5.0 MPa; |
| temperature at the inlet | 283-383 K; |
| mass flow rate of the fuel | 2000-9000 kg/(m$^2$·sec); |
| maximum heat flux density | 1.7 × 10$^6$ W/m$^2$. |

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 60, No. 1, pp. 46-50, January, 1991. Original article submitted August 2, 1989.



0022-0841/91/6001-0038$12.50 

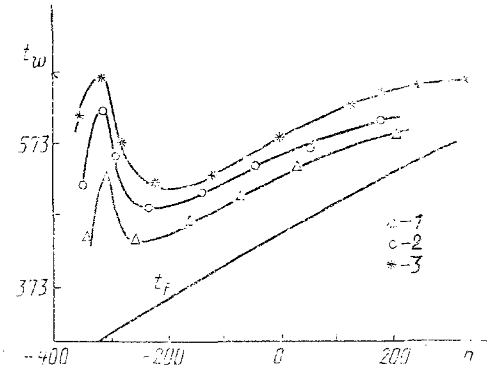


Fig. 1. The temperature of the tube wall (K) as a function of the enthalpy (kJ/kg) during the flow of fuel T-6 ($P$ = 5.0 MPa; $\overline{\rho w}$ = 9000 kg/(m$^2$·sec); $t_{in}$ = 373 K) for the following values of the heat flux density: 1) $q_w$ = 7.8·10$^5$ W/m$^2$; 2) $q_w$ = 9.3·10$^5$ W/m$^2$; 3) $q_w$ = 11·10$^5$ W/m$^2$.

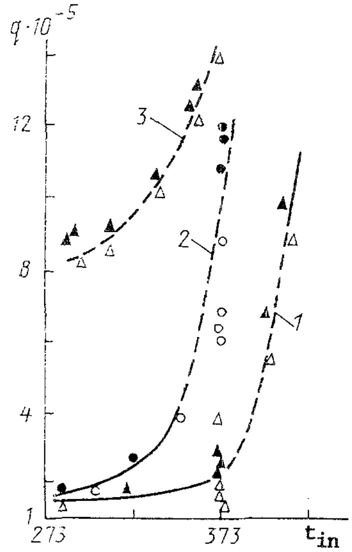


Fig. 2

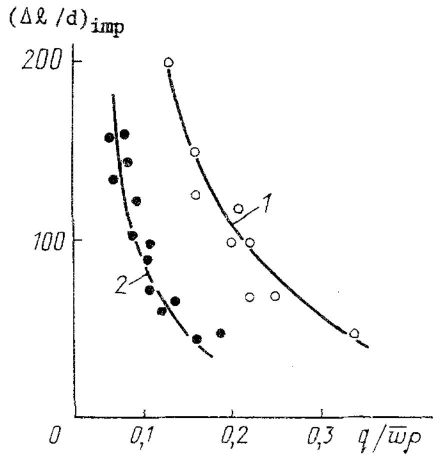


Fig. 3

Fig. 2. The "critical" heat flux density, W/m$^2$, as a function of the temperature, K, for fuel T-6 at the entry to the channel ($P$ = 5.0 MPa): 1) $\overline{\rho w}$ = 2200 kg/(m$^2$·sec); 2) $\overline{\rho w}$ = 4200 kg/(m$^2$·sec); 3) $\overline{\rho w}$ = 8800 kg/(m$^2$·sec).

Fig. 3. The relative length of the zone of impaired heat exchange as a function of the specific heat loading, kJ/kg. Fuel RT ($P$ = 5.0 MPa): 1) $\overline{\rho w}$ = 2300 kg/(m$^2$·sec); 2) $\overline{\rho w}$ = 4600 kg/(m$^2$·sec).

The results of the measurements of the temperature conditions in the tube are given in Fig. 1 in the form of relationships $t_w = f(h)$ for the fuel T-6 at a mass flow rate $\overline{\rho w}$ = 9000 kg/(m$^2$·sec). An analogous nature of the temperature conditions of the tube, with a zone of impaired heat exchange ending in a "surge" of the wall temperature $t_w$, was also found at the other mass flow rates both for the T-6 fuel and for the RT fuel. The unusual feature of the results obtained is that the regimes of impaired heat exchange occurred at relatively low temperatures of the flow: $t_{in}$ < 283-288 K for the RT fuel, and $t_{in}$ < 373 K for the T-6 fuel. The wall temperature peaks occurred at sections where $t_f \lesssim 303$ K (fuel RT) or $t_f \lesssim 403$ K (fuel T-6). This is the main difference of the results obtained here from most of the other studies with heat transfer media at SCP, where the zone of impaired heat exchange occurred only in the pericritical zone where $t_f < t_m < t_w$.

TABLE 1. Heat Flux Densities for Fuels RT and T-6

| Flow rate, $10^{-3}$ kg/sec | Mass flow rate, kg/($m^2$·sec) | Max. heat flux density in expt., kW/$m^2$ | "Critical" heat flux density, kW/$m^2$ | | | |
|---|---|---|---|---|---|---|
| | | | RT | | T-6 | |
| | | | $t_{in}$=283 K | $t_{in}$=373 K | $t_{in}$=283 K | $t_{in}$=373 K |
| 1,5...1,8 | 2000...2300 | 900 | 200 | — | 160 | 200 |
| 3,3...3,6 | 4200...4500 | 1400 | 440 | — | 180 | 820 |
| 6,6...7,0 | 8500...9000 | 1700 | — | — | 820 | 1600 |

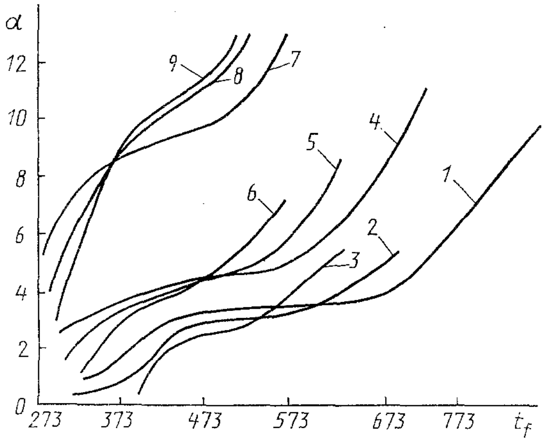


Fig. 4. Effect of the mass velocity, kg/($m^2$·sec), the heat flux density, W/$m^2$, and temperature, K, on the heat transfer coefficient, W/($m^2$·K), to the fuel T-6 at $\overline{\rho w}$ = 2300 kg/($m^2$·sec): 1) $q_w$ = 7.4·$10^5$ W/$m^2$; 2) $q_w$ = 4.8·$10^5$ W/$m^2$; 3) $q_w$ = 2.2·$10^5$ W/$m^2$; at $\overline{\rho w}$ = 4500 kg/($m^2$·sec): 4) $q_w$ = 11·$10^5$ W/$m^2$; 5) $q_w$ = 8.7·$10^5$ W/$m^2$; 6) $q_w$ = 5.0·$10^5$ W/$m^2$; at $\overline{\rho w}$ = 9000 kg/($m^2$·sec): 7) $q_w$ = 11.3·$10^5$ W/$m^2$; 8) $q_w$ = 7.8·$10^5$ W/$m^2$; 9) $q_w$ = 5.7·$10^5$ W/$m^2$.

The unusual nature of the impaired heat exchange which was observed was connected with the nature of the changes of the thermophysical properties of the fuels as the temperature changed. Although the density decreases particularly sharply in the pericritical region, there is a very rapid decrease in the dynamic viscosity in the zone of relatively small temperatures (up to 373 K), and this is much more rapid than for the other heat transfer media which have been studied [6].

This leads to the fact that in many regimes at small values of $t_f$ the density of the fuel at the wall temperature is 3-5 times smaller than the density in the core of the flow, while the viscosity is 50 times smaller. The reduction in the viscosity in the layer adjacent to the wall leads to a reduction in the wall shear stress which facilitates the laminarization of the layer adjacent to the wall and hence promotes the impairment of heat exchange.

The regimes of impaired heat exchange are observed $l/d \simeq$ 100-200; their occurrence is connected not with the conditions of entry into the channel, but to considerable nonuniformities of the flow at small temperatures of the fuels and specific relationships between the regime parameters $q$ and $\rho w$.

The boundaries of the regime of impaired heat exchange are shown in Fig. 2; the solid symbols correspond to the regime with impaired heat exchange, while the open symbols correspond to normal (monotonic) heat exchange. The extent of the zone of impaired heat exchange $(\Delta l/d)_{imp}$ depends on $q_w$, $\rho w$, and $t_{in}$ (Fig. 3). The minimum ("critical") values of the heat flux density leading to the appearance of the regime of impaired heat exchange are given in Table 1.

It can be seen that the "critical" heat flux density for the fuel T-6 is lower than that for the fuel RT, and increases with increase of the fuel temperature.

In order to define the conditions which cause the impairment of heat exchange let us consider the heat balance during the heating of the tube in accordance with a two-layer model of the flow, which is assumed to consist of a core and a layer adjacent to the wall:

$$q_w \pi d \Delta l_{\text{imp}} = (\overline{\rho w})_{\text{core}} (t'' - t')_{\text{core}} C_{p\,\text{core}} \frac{\pi d_{\text{core}}^2}{4} + (\overline{\rho w})_w (t'' - t')_w C_{pw} \pi d \delta_w. \tag{1}$$

Here the subscripts core and $w$ correspond to the parameters of the core and of the layer adjacent to the wall, and $t'$ and $t''$ are the temperatures and the beginning and end of the zone of impaired heat exchange ($\Delta l_{\text{imp}}$).

In turbulent flow under conditions of normal heat exchange the following relations apply beyond the stabilization zone:

$$(t'' - t')_{\text{core}} \simeq (t'' - t')_w = \Delta t$$

and

$$q_w \pi d \Delta l_{\text{imp}} = \overline{\rho w} \frac{\pi d^2}{4} C_p \overline{\Delta t}. \tag{2}$$

In the case of impaired heat exchange $\Delta t_w > \Delta t_{\text{core}}$, $\rho_{\text{core}} > \rho_w$.

Let us assume on the basis of the experimental data that in the regime of impaired heat exchange

$$\Delta t_w / \Delta t_{\text{core}} \approx \Delta t_w / \overline{\Delta t} \geqslant 2. \tag{3}$$

Then

$$\frac{\Delta t_w}{\overline{\Delta t}} = \frac{q_p \Delta l_{\text{imp}} / (\overline{\rho w} d C_p \Delta t)_{\text{core}} - 0{,}25}{\dfrac{(\overline{\rho w})_w}{(\overline{\rho w})_{\text{core}}} \dfrac{C_{pw}}{C_{\text{core}}} \dfrac{\delta}{d}} \geqslant 2,$$

from which follows the condition for impaired heat exchange

$$\frac{q_w}{\overline{\rho w}} \frac{\Delta l_{\text{imp}}}{d} \frac{1}{C_p \Delta t} \geqslant 0{,}25 + 2 \frac{(\overline{\rho w})_w}{(\overline{\rho w})_{\text{core}}} \frac{C_{\text{core}}}{C_{\text{core}}} \frac{\delta}{d}. \tag{4}$$

Thus, the appearance of the regime of impaired heat exchange is governed by the value of the parameter $q/\overline{\rho w}$ and the ratio of the velocities $(\overline{\rho w})_w/(\overline{\rho w})_{\text{core}}$ which depends on the ratio of the properties (density and viscosity) at the wall and in the core of the flow.

For an approximate evaluation it can be assumed that

$$(\overline{\rho w})_{\text{core}} = \overline{\rho w};\ (\overline{\rho w})_w / (\overline{\rho w})_{\text{core}} \simeq 0{,}6;\ C_{pw}/C_{\text{core}} \simeq 1;\ d_{\text{core}} \approx d,$$

in which case the condition (4) assumes the following form

$$\frac{q_w}{\overline{\rho w}} (\Delta l/d)_{\text{imp}} \frac{1}{C_p \overline{\Delta t}} \geqslant 0{,}3 \ldots 0{,}35. \tag{5}$$

The dependence of the heat transfer coefficient on the operating parameters in the zones of impaired and monotonic heat exchange is shown in Fig. 4. The increase in $\alpha$ as the fuel temperature increases is caused not only by the increase of the Reynolds number over the length of the tube but also by the decrease in the degree of nonuniformity of the stream, which is expressed by the ratio of the physical properties of the stream over the cross section, and in particular by the ratio $\mu_w/\mu_f$.

As the heat flux density increases the intensity of heat exchange in the zone of monotonic heat exchange decreases, while in the zone of impaired heat exchange, on the contrary, it increases.

For the same operating parameters the intensity of heat exchange to the fuel T-6 is lower than that to the fuel RT, as a result of the larger viscosity.

The experimental data on impaired heat exchange was generalized by the following dimensionless relationship to an accuracy of ±15%:

$$\mathrm{Nu} = 1{,}2\cdot 10^{-3}\,\mathrm{Re}^{1,3}\,(\mu_w/\mu_f)^{0,25}\,(x/d)^{-0,4}, \tag{6}$$

where $x/d < (\Delta l/d)_{imp}$. This relationship expresses the reduction in the intensity of heat exchange over the length of the zone of impairment $\Delta l_{imp}$, and shows a larger effect of the velocity than in the subsequent zone of monotonic heat exchange.

In the zone of monotonic heat exchange the experimental data for the fuels T-6 and RT were generalized by the following dimensionless relationship with an accuracy of ±20%:

$$\mathrm{Nu} = 0{,}04\,\mathrm{Re}^{0,72}\,\mathrm{Pr}^{0,4}\,(\mu_w/\mu_f)^{0,25}. \tag{7}$$

The data which have been obtained can be used for evaluating the conditions under which it is possible to form carbonaceous deposits from the fuel on the channel walls.

## NOTATION

Here $x$, $\Delta l$, $d$ are the longitudinal coordinate, length, and tube diameter; $t$, temperature; $\Delta t$, temperature difference; $P$, pressure; $h$, enthalpy; $q$, heat flux density; $\alpha$, heat transfer coefficient; $C_p$, isobaric heat capacity; $\rho w$, mass flow rate; $\mu$, dynamic viscosity; Re, Reynolds number; Pr, Prandtl number; Nu, Nusselt number.

## SUBSCRIPTS

$f$, fluid; $w$, wall; $m$, pseudocritical; core, core of stream; imp, impaired.

## SUPERSCRIPTS

′, ″, beginning and end of zone of impaired heat exchange; ¯ (overscore): averaged.

## LITERATURE CITED


1. I. Dzh. Setela, A. Dzh. Dzhinovanetti, and S. Koén, Énergeticheskie Mashiny i Ustanovki, No. 3, 22-28 (1986).
2. B. S. Petukhov, Current Problems in the Theory of Heat Exchange and Physical Fluid Dynamics [in Russian], Novosibirsk (1984), pp. 54-67.
3. F. I. Kalbaliev and G. I. Isaev, Inzh.-Fiz. Zh., **36**, No. 4, 742-743 (1979).
4. N. L. Kafengauz, Inzh.-Fiz. Zh., **44**, No. 1, 14-19 (1983).
5. E. P. Fedorov, L. S. Yanovskii, and V. I. Krasnyuk, Current Problems of Hydrodynamics and Heat Exchange in Energy Equipment Components and Cryogenic Engineering [in Russian], Sb. Nauch. Tr. Vsesoyuz. Zaoch. Mashinostr. Inst., Moscow (1986), pp. 10-17.
6. N. F. Dubovkin, V. G. Malanicheva, Yu. P. Massur, and E. P. Fedorov, Physicochemical and Usage Properties of Jet Fuels (Handbook) [in Russian], Moscow (1985), pp. 55-56.