HEAT TRANSFER IN HYDROCARBON FUEL BOILING UNDER CONDITIONS OF NATURAL CONVECTION

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Data on the heat-transfer coefficient in boiling of five jet fuels, two automotive gasolines, and a diesel fuel are presented over a wide range of regime parameters. The obtained results are described by a unified similarity equation.

Boiling as a high-intensity method of heat removal has widespread application in many industrial fields. Modern mechanical engineering is no exception here. It is common knowledge that in recovery of the heat released in an engine by the fuel itself its initial enthalpy increases, which leads to decreased specific fuel consumption and improved economical operation of the engine.

Certain advances in the theory of heat transfer in boiling have been achieved as applied to one-component liquids for which a series of models of the process has been proposed and criterial and empirical relations for calculating the heat-transfer coefficient have been obtained. Here we can put emphasis on D. A. Labuntsov's works [1-3]. Heat transfer in boiling of binary and ternary mixtures is studied in less detail. There are no developed models of the process in literature at all concerning complex multicomponent systems, such as hydrocarbon fuels produced by oil refining, and, to calculate similar systems, empirical relations of the form $\alpha = A(P_s) \cdot q^n$ are proposed where values of the factor $A(P_s)$ and the exponent n are determined experimentally and are valid only for the liquid in question.

The calculated relations obtained in [4, 5] for the heat-transfer coefficient in multicomponent mixture boiling include similarity numbers, in which concentrations of the components of the system in liquid and vapor phases appear. The latter circumstance does not enable us to use these relations for describing heat transfer in boiling of complex multicomponent mixtures, whose component composition is not always known.

This work gives the results of an experimental investigation into the process of pool boiling of TS-1, RT, T-6, T-8, and T-8V jet fuels, A-76 and Ai-93 automotive gasolines, and a diesel fuel that are complex multicomponent hydrocarbon mixtures. Because we do not know the component composition of the fuels we considered them as pseudo-one-component systems. To run the experiments, we installed a cylindrical tank of stainless steel (Fig. 1). A tube of IXI8H9T stainless steel 6.67 × 6.00 mm in diameter and 127 mm long served as the heating surface. A condenser and a window that served to illuminate the interior portion of the plant were attached to the tank's lid. The outside of the tank was wrapped with a compensating heater and heat insulation. The condensate from the condenser ran off through a jacket placed above the boiling liquid into a special branch, where it was heated to the saturation temperature and entered the boiling medium again. The phase volume relation was $V_v / V_{liq} = 3/5$ before the experiments. For this relation, as was shown in [6], the change in the liquid phase mass does not exceed 0.3% over the entire intervals of investigated temperatures and pressures. This enables us to state that all experimental points for any fuel are obtained with the same fractional composition.

In trial experiments in boiling of the fuels in question we observed their intense darkening, and a resinous layer that had a pronounced effect on the heat transfer process formed on the heating surface. The formation of this layer is due to the action of elevated temperatures [7] and the presence of dissolved oxygen in the fuels. To eliminate this effect, we removed the oxygen, i.e., deoxygenated the fuel: prior to the experiment nitrogen was bubbled for 6−8 h through the fuel poured into the tank. The process of treatment enabled us to retain the constant fractional composition of the fuels during the experimental time. Thus, in boiling of the TS-1 jet fuel (Fig. 2) for
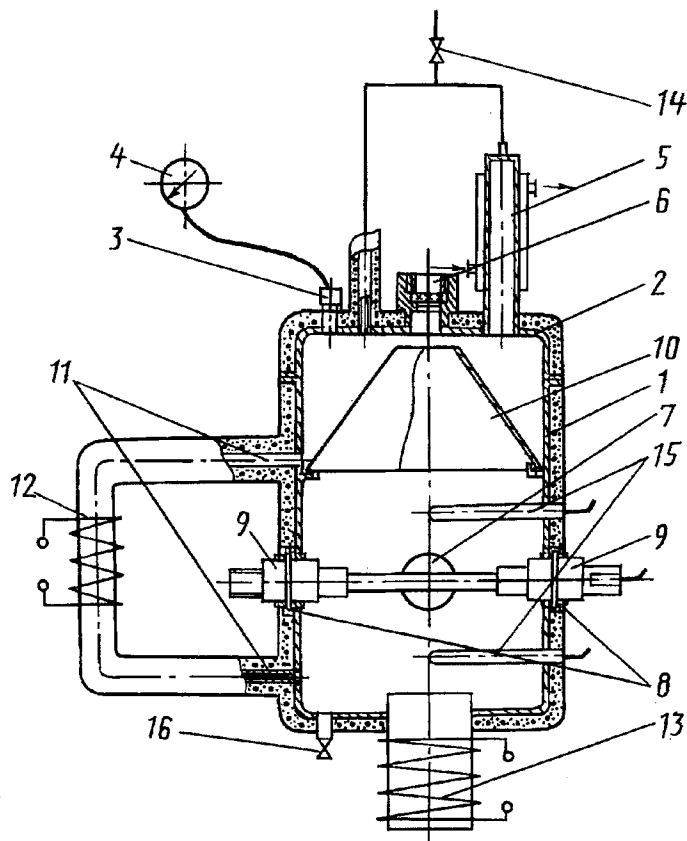

Fig. 1. Schematic of the experimental setup: 1) tank; 2) lid; 3) connecting pipe for the manometer tube and filling the plant with a liquid; 4) reference manometer; 5) condenser; 6) window for illuminating the inner surface of the chamber; 7) peepholes for visual observation; 8) connecting pipe with special gaskets; 9) copper tips of the heater; 10) cone-shaped insert for the condensate runoff; 11) circulation branch for the condensate runoff; 12) heater for heating the condensate; 13) heater for bringing the liquid to a saturation temperature; 14) cock for discharging displaced gases; 15) cases with thermocouples to measure the liquid temperature; 16) cock for the liquid drainage.

120 h with a constant heat flux a decrease in the heat-transfer coefficient did not exceed 8% and complete darkening of the fuel came only within 200–210 h after the commencement of the experiment while in the untreated fuel we observed a drastic decrease in α and darkening of the liquid in question even in the first hours. The drastic decrease in the heat-transfer coefficient within 120 h of operation can be explained by the fact that during this time interval the value of deposits attains a certain thickness on nucleation sites and the process of collapsing of these sites commences. While earlier heat transfer occurred mainly between the wall-liquid systems, the wall-resin-liquid system comes into play within 120 h. The process of collapsing lasts for 30–40 h, after which the curve levels off again but at a different level and heat transfer occurs only between the wall-resin-liquid systems. The further decrease is explained only by a growth in the resinous layer thickness, i.e., the influence of its thermal conductivity.

Based on the results of this experiment the duration of the experiment was restricted to 30–40 h in each run. After the liquid had been drained the inner surface of the plant and the tube surface were cleansed of the traces of the previous experiment using acetone, n-hexane, and water. Furthermore, before the next liquid in question was poured it was rinsed with some amount of this fuel.

The maximum relative measuring error in the experiments did not exceed ±4% for the heat flux and ±7% for the heat-transfer coefficient. The experiments were carried out at pressures from 0.1 to 1.1 MPa for the TS-1, RT, and T-8 jet fuels, A-76 and Ai-93 gasolines, to 1.0 MPa for the T-8V jet fuel, and to 0.6 MPa for the diesel
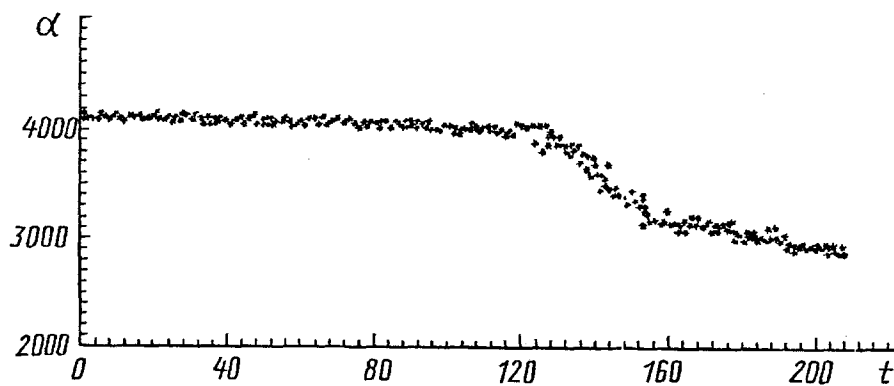
Fig. 2. Heat-transfer coefficient as a function of experimental time in boiling of TS-1 jet fuel, $P_s = 2$ bar, $q = 125$ kW/m^2. α, W/(m$^2\cdot$K); t, h.

TABLE 1

Coefficient	TS-1	RT	T-6	T-8	T-8V	A-76	Ai-93	Diesel Fuel
B	57.83	59.34	59.05	57.62	60.84	51.43	51.58	53.62
N	230.7	253.2	182.6	213.1	246.9	279.3	266.9	137.7

Таблица 2

P_s, MPa	TS-1		RT		T-6		T-8	
	A	n	A	n	A	n	A	n
0,1	0,551	0,745	0,368	0,776	0,664	0,719	0,328	0,778
0,2	0,755	0,733	0,615	0,747	1,095	0,690	0,451	0,768
0,3	1,015	0,716	0,805	0,733	1,515	0,672	0,653	0,747
0,4	1,278	0,703	0,962	0,723	1,761	0,665	0,884	0,732
0,5	1,495	0,696	1,126	0,718	1,871	0,663	1,013	0,725
0,6	1,643	0,695	1,312	0,710	2,078	0,658	1,179	0,719
0,7	1,942	0,684	1,505	0,702			1,291	0,715
0,8	2,392	0,670	1,748	0,694			1,504	0,704
0,9	2,460	0,670	2,128	0,681			1,664	0,698
1,0	2,903	0,657	2,198	0,680			1,803	0,695
1,1	3,097	0,655	2,414	0,674			2,155	0,682

P_s, MPa	T-8V		A-76		Ai-93		Diesel Fuel	
	A	n	A	n	A	n	A	n
0,1	0,519	0,741	0,502	0,764	0,590	0,752	0,562	0,743
0,2	0,666	0,736	0,641	0,751	0,739	0,741	0,721	0,728
0,3	0,896	0,722	0,804	0,739	0,891	0,733	0,847	0,719
0,4	1,107	0,714	0,959	0,731	1,102	0,723	1,082	0,704
0,5	1,367	0,700	1,134	0,724	1,242	0,720	1,203	0,701
0,6	1,596	0,690	1,302	0,719	1,420	0,716	1,340	0,697
0,7	2,090	0,670	1,621	0,706	1,761	0,704		
0,8	2,319	0,666	2,050	0,692	2,104	0,696		
0,9	2,627	0,660	2,293	0,690	2,408	0,691		
1,0	3,171	0,649	2,564	0,687	2,859	0,683		
1,1			3,192	0,674	3,363	0,676		

fuel and T-6 jet fuel. As was noticed during the experiments, a nucleate regime developed with $q \approx 35-40$ kW/m^2 for the TS-1 jet fuel and gasolines and with $q \approx 45-70$ kW/m^2 for the other systems. This difference is explained by different thermophysical properties of the fuels. A similar picture was also observed in the nucleate-to-film boiling transition. While for the gasolines burn-out occurred with $q \approx 150-160$ kW/m^2 and for the TS-1 jet fuel with $q \approx 210-220$ kW/m^2, for the other fuels the nucleate regime persisted with $q \approx 230-250$ kW/m^2.
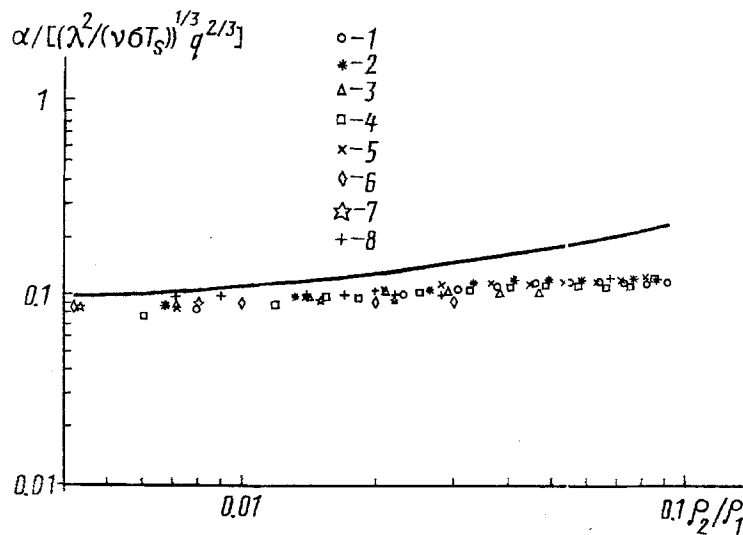
Fig. 3. Comparison of the experimental data (points) with D. A. Labuntsov's model [3] (curve): 1) TS-1 fuel; 2) RT; 3) T-6; 4) T-8; 5) T-8V; 6) A-76; 7) Ai-93; 8) jet fuel.
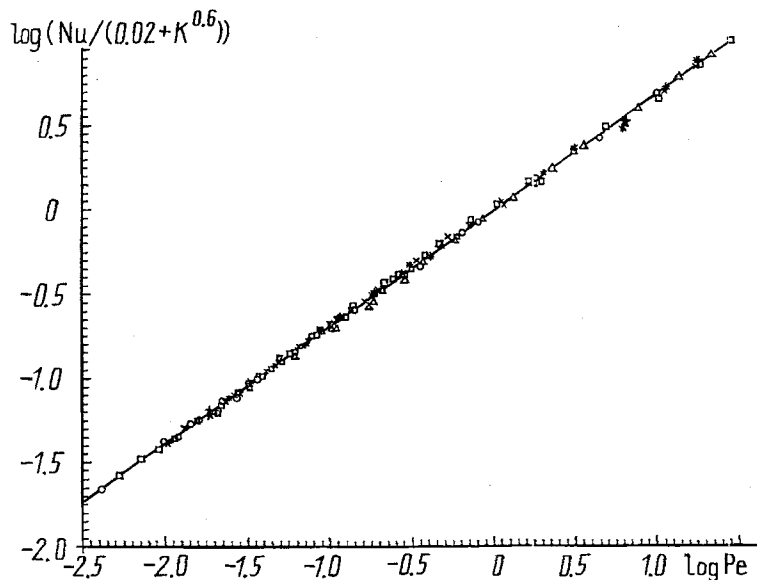

Fig. 4. Comparison of the experimental data with expression (3). The designation is the same as in Fig. 3.

The boiling point of the systems as a function of the saturation pressure can be described by the empirical dependence

$$T_s = B \ln (P_s) - N,$$ (1)

whose coefficients B and N as functions of the fuel specification are given in Table 1.

We determined the heat-transfer coefficient for 10–20 values of the heat flux density at each pressure. This enabled us to calculate with high accuracy the coefficients of the empirical dependence of the form $\alpha = Aq^n$ (see Table 2).

As we can see in using this dependence the values of the coefficients A and n are affected both by the pressure and properties of the liquid itself, which makes it difficult to obtain one calculated empirical dependence for all the fuels. This led to an attempt at generalizing the experimental results using thermophysical properties of the systems that were taken from handbooks [8-10].

As has been already noted models developed by D. A. Labuntsov are the most universally accepted models in one-component liquid boiling. Figure 3 compares the data obtained on all the systems with the equation

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$$\alpha = 0.075 \left[1 + 10 \left(\frac{\rho_2}{\rho_1 - \rho_2} \right)^{2/3} \right] \left(\frac{\lambda^2}{\nu \sigma T_s} \right)^{1/3}, \qquad (2)$$

obtained in [3]. As the figure shows our points fell below the curve for the one-component systems but if we replace by 3 the correction factor of 10 in (2), we form the basis for calculating the heat-transfer coefficient in boiling of jet and diesel fuels with not more than $\pm 25\%$ error for the parameter range in question. The gasolines are better described by relation (2) if we take 0.06 as the factor before the brackets and with a correction factor of 5. In this case the scatter of points does not exceed $\pm 20\%$.

In connection with the fact that the scatter of points in this generalization turned out to be dependent on the nature of the liquids themselves and it is unlikely that this percent of the error will suit today's needs of mechanical engineers a further generalization was performed with the aim of obtaining a calculated dependence that would describe the results of measurements with a smaller error. As the analysis showed the experimental results are described with the best accuracy by the calculated dependence

$$Nu = \left[0.02 + \left(\frac{r \rho_2}{C_p T_s \rho_1} \right)^{0.6} \right] Pe^{0.7} \qquad (3)$$

(see Fig. 4). The deviation of the results does not exceed 15%. The latter expression also describes the results of V. A. Zhavoronkov's experiments [11] carried out under vacuum with VM-1, VM-3, and VM-5 vaccum oils within an error of $\pm 20\%$.

NOTATION

α, heat-transfer coefficient, $W/(m^2 \cdot K)$; P_s, pressure, MPa; q, heat flux density, W/m^2; V, volume, m^3; T_s, temperature, K; ρ_1 and ρ_2, density of the liquid and vapor phases, kg/m^3; λ, thermal conductivity, $W/(m \cdot K)$; λ, viscosity of the liquid, m^2/sec; σ, surface tension, N/m; C_p, heat capacity, $J/(kg \cdot K)$; r, vaporization heat, J/kg; Nu, Nusselt number; P, Pecklet number. $l = C_p T_s \sigma \rho_1 / (r \rho_2)^2$ serves as a governing dimension.

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