BEHAVIOR OF A FUEL OIL DROPLET ON A HOT SURFACE

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Combustion of a fuel oil droplet on a hot oblique surface, whose temperature varies between 350 and 700°C, has been studied experimentally. The influence of the heat conductivity of the wall and its roughness, as well as of the droplet-surface contact angle on the fuel combustion time has been determined. The data on the change in the droplet mass in the process of combustion are presented and chromatographic analysis of the fuel has been performed.

Introduction. Combustion of a fuel oil droplet freely flying in a hot medium has been studied fairly widely and broken up into several stages. The first stage is droplet heating. Components, whose boiling temperature is comparatively low, evaporate not only from the surface but also from the center of the droplet. During this stage the droplet is often inflated. The released volatile substances ignite, and the additional heat determines the further decomposition of the fuel. Upon burning of volatile substances, more viscous compounds remain and form a spatial porous residue. Its burning time is equal to about half of the whole lifetime of the droplet [1, 2]. It has been established that with increasing temperature the combustion phase of the carbon residue becomes dominant and the residue itself becomes less porous and harder [3, 4]. Combustion of the fuel oil carbon residue can be compared to solid fuel combustion. In [1, 5, 6], it was shown that at low temperatures and small particles evaporation of volatiles and heterogeneous combustion of a carbon particle occur simultaneously, since the concentration of oxygen is comparatively large. Not only surface but also internal combustion is possible. With increasing temperature or increasing particle diameter, homogeneous combustion of volatile substances occurs at a distance from the particle surface, which impedes the inflow of oxygen, and internal combustion is retarded. However, the burning hydrocarbons heat the particle surface, where pyrolysis and polymerization are observed. Moreover, during combustion of volatiles the particle or fuel oil temperature strongly increases, and because of the thermal stresses particle fragmentation is possible [1, 6, 7].

Sometimes in technological facilities, cases where the fuel droplet interacts with a solid surface are observed. Because of the deficiency of heat, the droplet of a fuel oil containing about 85% carbon burns only partially; therefore, after some time on the surface a coke layer impairing the operation of the facility is formed.

The droplet–surface interaction is being studied extensively. The photographs presented in [8, 9] show the dynamics of a droplet impacting a surface. It has been found that the physical properties of a liquid, as well as the rate of motion of a droplet, determine whether the droplet will break up into several smaller parts or will bounce from the surface as a whole mass. The influence of wall parameters, such as its temperature, roughness, and physical properties, on the behavior of a fuel droplet and its evaporation time is also investigated [10, 11]. The interaction of a droplet with a solid surface is simulated with the use of different codes that take into account the liquid properties, the wall parameters, and the wall–liquid heat transfer. Comparison of calculated data with experimental ones shows a good agreement [12, 13].

Despite the large body of experimental data, the information on the fuel droplet evaporation from a hot surface is still insufficient. This paper presents the results of experiments on fuel oil droplet combustion on surfaces with a different heat conductivity — quartz and steel. Since wall roughness improves the liquid–surface heat transfer, we formed transverse and pyramidal elements of roughness on a steel surface. Data on the fuel combustion on an oblique surface are also given. It has been established experimentally that in the process of combustion the fuel-oil-droplet mass changes, and, in addition, chromatographic analysis of the fuel has been performed.
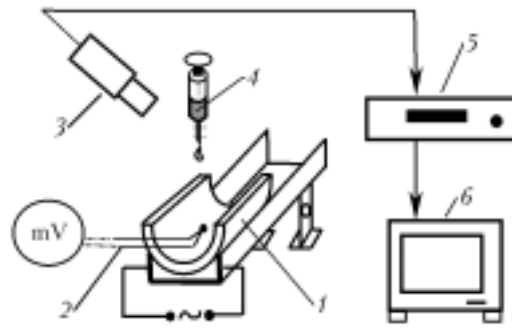
Fig. 1. Experimental test bed: 1) steel or quartz trough; 2) thermocouple; 3) video camera; 4) syringe with fuel oil; 5) video tape recorder; 6) TV set.
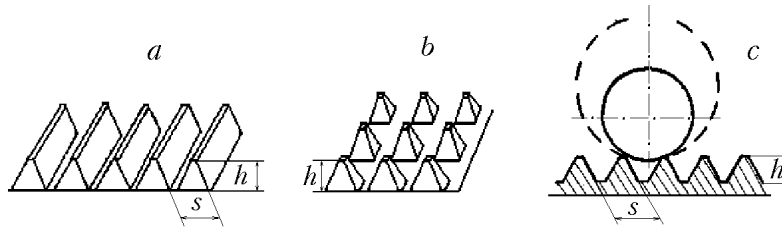

Fig. 2. Schematical representation of the surfaces used (a, b) and of the fuel oil droplet fallen on them (c).

Measuring Procedure. For investigations, we used market fuel oil (density of 970 kg/m^3, specific heat capacity of 2000 J/(kg·K), kinematic viscosity of $118 \cdot 10^{-6}$ m^2/sec, combustion heat of 40,500 kJ/kg, flash temperature of 95°C; elemental composition: C = 86%, S = 2.5%, H$_2$ = 10.5%, ash content of 0.04%, water and mechanical impurities of less than 1%). During all experiments the fuel oil temperature was maintained at a level of 76°C.

For the investigations, we designed a test bed (Fig. 1) where quartz and steel troughs of radius 30 mm and length 100 mm were used. The troughs were placed in a light-weight brick, on whose bottom a nichrome spiral connected to the autotransformer contacts was located. The brick with troughs was mounted on a panel, one of whose ends was fixed and the other of which could be lifted to the desired height and fixed.

The heat-conductivity coefficients of steel and quartz are, respectively, 42 and 1.3 W/(m·K), and their thermal diffusivities are $12 \cdot 10^{-6}$ and $3.3 \cdot 10^{-6}$ m^2/sec.

The surface temperature was measured with the help of a chromel-alumel thermocouple connected to a digital voltmeter. The fuel oil was dosed by a syringe with a needle of diameter 0.60 $\pm$ 0.01 mm. For the droplets to be identical during all experiments, only the sixth or one of the following droplets was directed onto the surface, i.e., when the flow from the needle became steady. The mass of the fuel oil was calculated by the mass difference principle: a sheet of paper, whose mass was known in advance, was repeatedly weighted after only one fuel oil droplet was directed onto it. The mean mass of the fuel oil droplet was measured to be 3.3 $\pm$ 0.1 mg (error of ~3%), and the calculated diameter was ~2.3 mm. The combustion process was taken with a CCD video camera with a 632 × 512 photocell matrix. To view and analyze the video records, we used a Sony SLV-X712 tape recorder. Viewing of a high-speed frame took 40 msec. The combustion time of the carbon residue was registered by a stopwatch.

To determine the carbon residue mass, we used a piece of quartz glass of mass 532.05 $\pm$ 0.02 mg. We also determined the temperature interval (from 550 to 650°C) in which three characteristic forms of the residue were formed. The quartz with the remaining unburnt mass was cooled and weighed at different instants of time: 2–3 sec after the fuel oil droplet struck the surface, i.e., upon evaporation of the major portion of volatiles and carbon residue formation, and 8–10 sec after the fuel oil droplet struck the surface. In the first case, the calculated mass of the carbon residue was equal to 0.28 mg on average with an error of 14%, and in the second case — 0.05 mg with an error of 60%.

To estimate the influence of the surface roughness, we used two steel surfaces with transverse notches and two surfaces with pyramid notches — four troughs in all (Fig. 2). From several levels of heights of roughness ele-
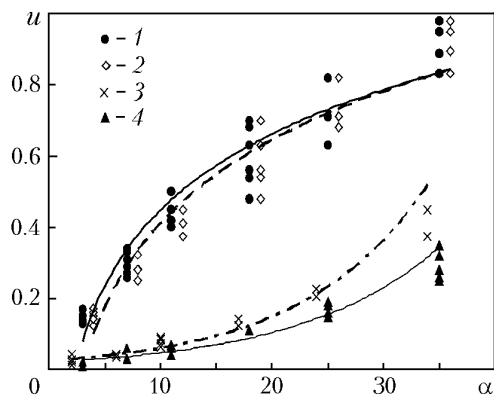
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Fig. 3. Droplet velocity versus the surface slope: 1) steel; 2) quartz; 3) pyramidal notches (h = 0.68 mm); 4) transverse notches (h = 0.68 mm). T = 500°C. u, m/sec; α, deg.
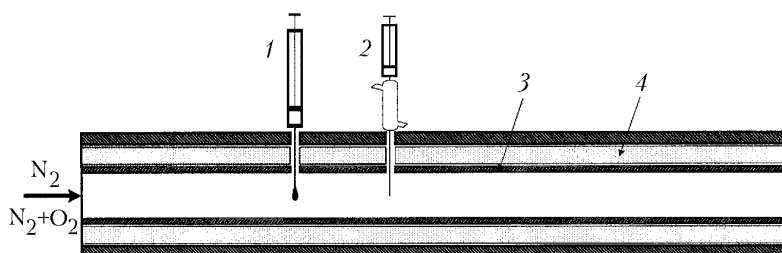

Fig. 4. Bench for fuel oil gasification under different ambient conditions upon fuel oil injection by drops: 1) fuel oil injection point; 2) sampling point; 3) quartz glass tube; 4) heat insulation.

ments we chose two that produced a marked effect on the process of droplet combustion. In either case (for pyramid and transverse notches), they were equal to 1/3 and 1/5 of the droplet diameter or 0.68 $\pm$ 0.01 mm and 0.43 $\pm$ 0.01 mm, respectively (Fig. 2a, b). The distances between the roughness elements s are 0.08 $\pm$ 0.01 mm (for h = 0.43 mm) and 1.25 $\pm$ 0.01 mm (for h = 0.68 mm).

As the surface slope was varied between 3 and 35°, the angle of droplet–wall contact changed from 87 to 55°. Because of the slope and the vapor film formation, the moving droplet picks up a particular velocity, which is approximately the same at different temperatures (Fig. 3).

Method of Chromatographic Investigation of Fuel Oil Gasification Products. For chromatographic analysis of combustion products — fuel oil pyrolysis — we devised a special reactor (Fig. 4). A quartz tube with an inner diameter of 18 mm and a length of 500 mm was wrapped in heating wire, insulated with heat-resistant glass-fiber wool, and placed in a steel tube of diameter 70 mm. In the reactor and the quartz tube, two holes spaced 50 mm apart were made. Through one of them about 15.6 mg of the fuel oil was injected, and through the second one, with a cooled sealed syringe of volume 2 ml, we took a sample of gasification products and introduced it directly into the gas chromatograph injector. The fuel was held in the hot zone for about 0.13–0.17 sec. First nitrogen and then a mixture of nitrogen with 4% oxygen and air were introduced into the reactor. The flow rate of the gas or its mixture was about 0.35 m/sec. The flow temperature was measured by a chromel-alumel thermocouple at the fuel oil injection point. For experiments, we chose two temperatures: 600°C, as in the above-mentioned experiment, and 1000°C.

Analysis of the samples was performed with the use of a Varian GC-3800 gas chromatograph equipped with a flame-ionization detector and a mass-spectrometer with an ion trap. We also used a universal 30-mm-long Varian VA-5ms capillary column of diameter 0.25 mm with a 0.25-μm-thick methylpolysiloxane (5% phenol) active layer. The other parameters of the experiment were as follows: the injector temperature was 250°C; the column temperature was varied from 25°C (5 min) to 250°C, held for 20 min at a rate of 5°C/min, and the rate of flow of the carrier gas (helium) through the column was 1.2 ml/min.
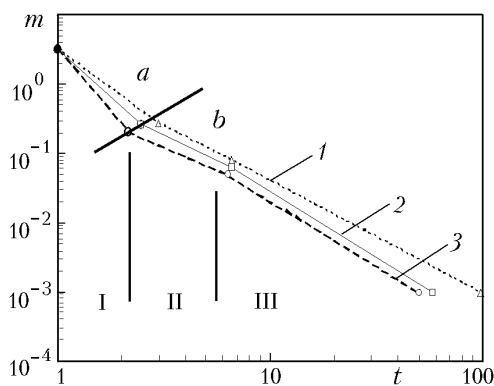
Fig. 5. Change in the fuel oil droplet mass in the process of combustion: 1) T = 560; 2) 620; 3) 650°C [a) evaporation of volatiles; b) carbon residue burn-up]. m, mg; t, sec.

The proposed method for analyzing the aromatic hydrocarbons obtained from the carbon ash extract was based on [14], and separation of hydrocarbons was carried out by the standard methods presented in [15]. The presence of inorganic gases and combustion products was ignored.

Results and Discussion. The fuel oil droplet falling on a surface whose temperature is above 350°C passes through all stages of combustion: heating, evaporation and ignition of volatiles and the formation of carbon residue and its heterogeneous combustion. Because the droplet receives a large portion of heat due to the heat conduction from the wall, the heat transfer between the surface and the liquid (droplet) can be described by the heat-conduction equation

$$\frac{\partial T}{\partial T} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right),$$

where $a = \lambda/\rho c$ is the thermal diffusivity: the higher it is, the faster the temperature equalization in the wall and thus the faster the fuel droplet combustion.

Impacting the wall, the fuel oil droplet deforms and in less than 40 msec regains its original spherical shape and hovers over the vapor cushion. On a steel surface with a large heat-conductivity coefficient λ, it forms already at a temperature of 350°C, and on a quartz surface — only at 420°C or higher. During evaporation of volatiles the droplet diameter almost doubles. The fuel oil temperature gradually increases, and the surface tension and thickness of the vapor cushion layer decrease. The droplet gradually spreads on the surface. Depending on the temperature, this process takes from 0.4 to 0.8 sec. At temperatures below 550°C, the spread fuel oil droplet on both the quartz and the steel surface forms a film, whose size is equal to about 2–3 initial diameters of the droplet. The lower layer is heated faster and the compounds of small molecular weight merge and, forming bubbles, are released from the mass as a light gas–nucleate boiling occurs. Upon evaporation of most volatiles (which takes from 1.5 to 0.6 sec on average), more viscous compounds remain and form a porous spatial carbon residue. According to [6], the carbon–oxidizer interaction involves intermediate unstable formations, which for a more or less long time stay in the adsorbed state on the outer surface of the carbon mass and on the pore surface. Their reactions with the oxidizer and between one another "retard" the combustion process, but the increasing porosity of the carbon particle enhances the oxygen inflow into its inner surface.

As mentioned above, we performed experiments to determine the changes in the droplet mass in the process of combustion (Fig. 5). At each point at least six measurements were made, but only the mean values are given on the graph. After the first 2–3 sec, when the vigorous boiling and evaporation of volatiles terminate, on the surface a metastable carbon residue that is formed is seen. Its mass constitutes about 10% of the initial mass of the droplet. In the subsequent 6–7 sec, the mass decreases additionally by a factor of five and constitutes only 2% of the initial mass. In this time interval, the form of the metalayer remains practically unchanged, and its combustion time constitutes, on average, 70–80% of the whole time of existence of the droplet on the hot surface. From these
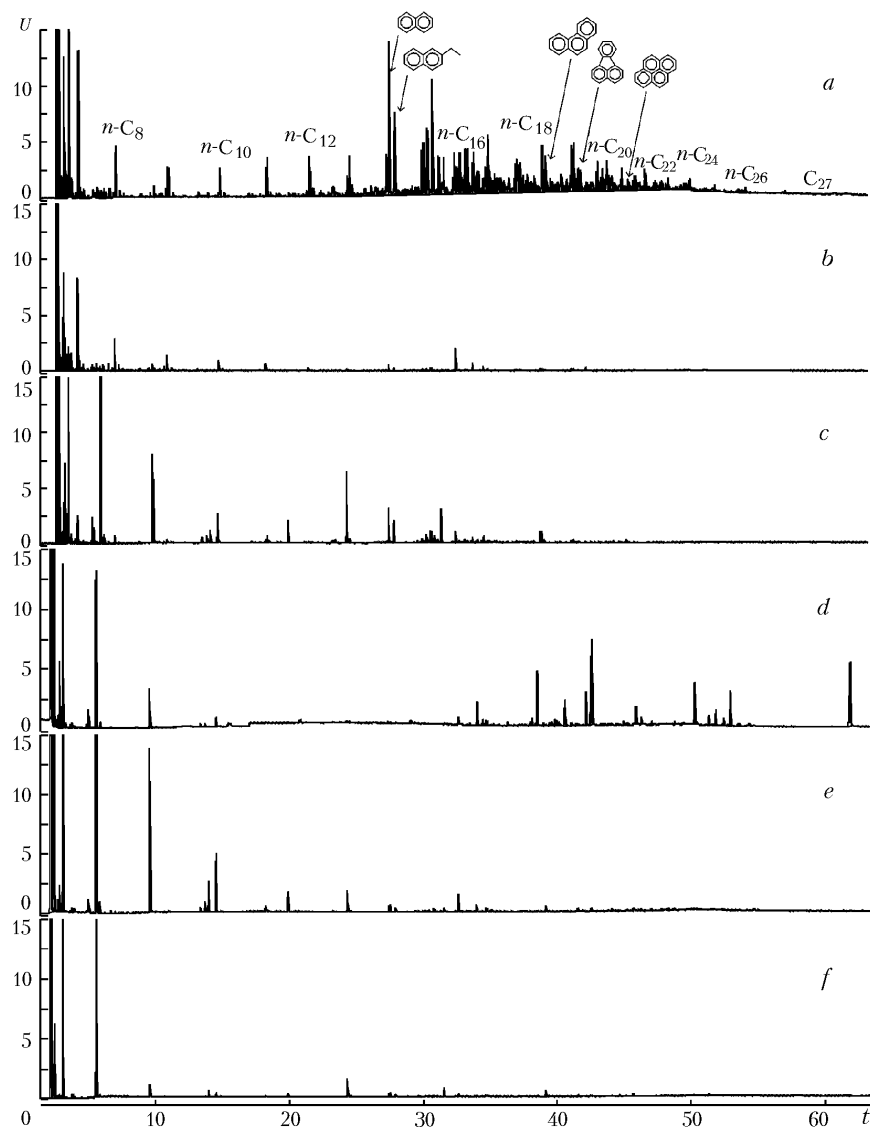
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Fig. 6. Chromatograms of fuel oil gasification products at $T = 600^{\circ}$C (a–c) and $T = 100^{\circ}$C (d–f) in different media: a and d) in nitrogen; b and e) in nitrogen diluted with 4% of oxygen; c and f) in air. U, mV; t, min.

data it is seen that the fuel oil droplet combustion on the surface consists of two phases — evaporation of volatiles (I) and coke combustion. Once a change in the mass has taken place, we conventionally break up the latter phase into two more stages: metalayer decomposition (II) and heterogeneous combustion of the carbon residue (III) (Fig. 5). The changes in the volatile and coke (carbon residue) masses can be given by the following dependences: $m_{\mathrm{v}} = 3.2t^{-0.36}$ and $m_{\mathrm{c}} = 0.5t^{-0.6}$.

To see what chemical transformations take place in the fuel when the oil droplet strikes a hot surface, we performed a gas-chromatographic analysis. The chromatograms of the gasification and combustion products in the reactor at a temperature of 600 and 1000°C are given in Fig. 6. Obviously, in the inert medium (Fig. 6a, d) vigorous evaporation and decomposition of the fuel oil components occur. In Fig. 6a one can see periodically recurring chromatographic peaks of aliphatic hydrocarbons C_8–C_{28}, where their isomers, alkenes, and aromatic hydrocarbons with two, three, and four C_6–C_{18} rings are also present. Such a multicomponent composition is formed under the action of temperature and is a source material for the subsequent oxidation reactions. The decomposition process — breaking of the C–C chains of aliphatic hydrocarbons — proceeds with the absorption of a large quantity of heat [16],
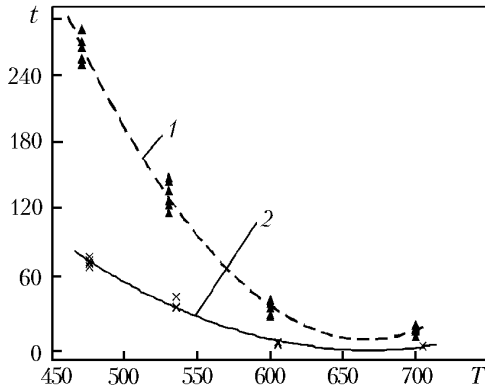
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Fig. 7. Combustion time of the fuel oil droplet of diameter 2.3 mm versus the surface temperature: 1) quartz surface; 2) steel surface. t, sec; T, $^{\circ}$C.
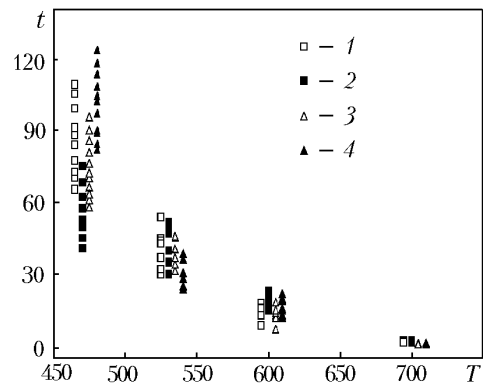
Fig. 8. Combustion time of the fuel oil droplet of diameter 2.3 mm versus the temperature of the surface with transverse (1, 2) and pyramidal (3, 4) roughness elements of different height: 1, 3) $h = 0.43$; 2, 4) 0.68 mm. t, sec; T, $^{\circ}$C.

and here an important role is played by the energy that the fuel receives not only due to the heat conduction from the side of the wall but also by convection and radiation. The intensive reactions at the initial stage with the presence of oxygen are exothermal and compensate, to a certain extent, the heat needed for the decomposition reactions through radicals. The presence of oxygen prevents the growth of aromatic rings in the initial phase of evaporation and combustion, and therefore, oxidation reactions proceed (Fig. 6b, c). At a higher temperature this process becomes particularly pronounced (Fig. 6e, f). At a temperature of 1000°C, there is a shift of pyrolysis products toward light hydrocarbons, especially methane, with the absorption of the fuel hydrogen. The conditions for the formation of hydrocarbons with a large quantity of carbon are created (Fig. 6d). It may be suggested that the remaining part of carbon promotes the coke formation from the polycyclic aromatic compounds of the gas phase. At a temperature of 1000°C with increasing concentration of oxygen in the gas mixture, the tendency toward heavy residue combustion is apparent. In other words, the larger the oxygen inflow and the higher the temperature, the better the combustion of the germ of the coke formation.

In the experiments with quartz and steel surfaces at a temperature above 600°C, splitting of the droplet into several smaller parts is observed. Because of the fast "release" of volatiles, the fuel oil droplet, having struck the steel surface, after about 0.6–1.0 sec breaks into small parts. The smallest of them, upon repeated strikes against the surface, stick to it and burn up within a few seconds, and particles with a larger diameter are prone to additional "explosion." The total burn-up time of a fuel oil droplet of diameter 2.3 mm on the steel surface at a temperature of 600°C is about 4 sec. As the temperature is increased to 700°C, besides the droplet "explosion," ignition of evaporated volatiles is also observed. The heat emitted by the flame increases the rate of carbon residue burnup. On the quartz glass, whose heat conductivity is smaller, "explosion" is observed only at a temperature of 700°C, and at 600°C only splitting of the droplet into two, three, and, less frequently, into four relatively equal parts occurs. Since the droplet fallen on the surface locally cools it, an important role is played by the heat conductivity λ of the wall — the larger the value of λ, the faster the equalization of the temperatures in the wall under the droplet. In the case with steel, the temperature difference is insignificant, and for the quartz it is about 70°C; therefore, the fuel combustion (Fig. 7) throughout the temperature range occurs several times faster on the steel surface. If we take into account the quartz cooling, then the time of droplet evaporation from these surfaces will be approximately the same, except for the time delay, because of which the droplet spreads on a larger area of the quartz surface.

The further experiments aimed to study the influence of the wall roughness on the fuel burn-up time. The fuel oil droplet that has struck a rough surface contacts it only at several points (see Fig. 2c). The roughness elements formed restrict the evaporation of volatiles and, therefore, they begin to act as a reactive lifting force, pushing or tossing the droplet up. Having repeatedly struck against the surface, the droplet deforms, and the asperities situated under it can promote its splitting into several parts.
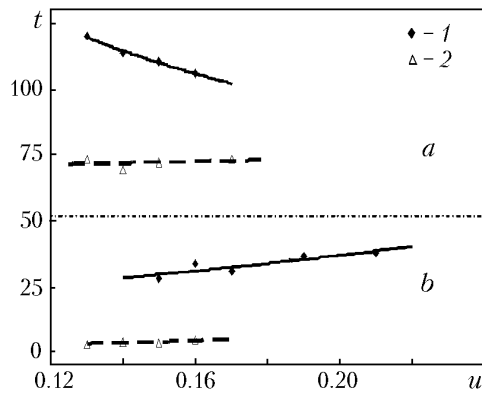
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Fig. 9. Combustion time of the fuel oil droplet of diameter 2.3 mm versus the rate of its motion on oblique quartz (1) and steel (2) surfaces at temperatures: a) below 550°C; b) above 550°C. t, sec; u, m/sec.
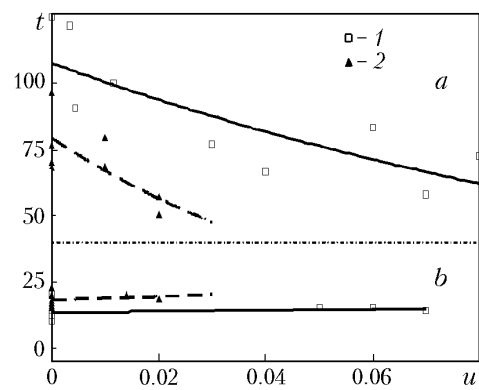
Fig. 10. Combustion time of the fuel oil droplet of diameter 2.3 mm versus the rate of its motion on an oblique rough surface at temperatures: a) below 550°C; b) above 550°C [1] pyramidal notches ($h = 0.43$ mm); 2) transverse notches ($h = 0.68$ mm). t, sec; u, m/sec.

At a temperature below 550°C, the fuel oil droplet burns up faster on a surface with roughness elements whose height h is 0.68 mm (Fig. 8). This can be explained by the fact that at such temperatures a porous spatial carbon residue is formed, and the high roughness elements (transverse at a temperature of 470°C and pyramidal at 530°C) determine the larger contact area of the carbon residue with the hot surface and thus promote its burnup. At a temperature above 550°C, the fuel oil droplet burns up faster, though insignificantly, on surfaces with smaller roughness elements ($h = 0.43$ nm). An increase in the surface temperature promotes the process of evaporation of volatiles, which, as mentioned above, begin to act as a lifting force. Therefore, the droplet is thrown up and after repeated contact with a hot rough surface splits into several parts. The small roughness elements do not impede the inflow of oxygen to the several carbon residues formed, which are smaller in size and burn up faster. However, despite the mass division, the droplet "explodes" only as the temperature of the rough surface is increased to 700°C, as in the case of quartz.

Comparing the results of the fuel oil droplet burnup on the rough and smooth steel surfaces, note that the positive effect of roughness, i.e., a decrease in the droplet burn-up time by up to 25%, shows up only at temperatures below 550°C, which in real facilities is a rare case.

The experiments with an oblique surface (when the angle of contact of the droplet with a hot surface is changed) show that on quartz at temperatures below 550°C with increasing droplet velocity its burn-up time decreases (Fig. 9). This can be attributed to the fact that the droplet wets the surface and the mass is distributed over a larger area. An increase in the temperature leads to the formation of a vapor cushion separating the droplet from the wall and thus prolonging the burn-up time of the droplet. On the steel surface a vapor cushion is formed at a temperature of 350°C. Therefore, the higher the fuel oil droplet velocity, the longer the time of its combustion throughout the temperature range (Fig. 9). At temperatures below 550°C, the fuel oil droplet, moving on an oblique rough surface, wets the wall, as in the case of quartz. The roughness elements stimulate destruction of the droplet and, therefore, its burn-up time decreases by up to 40% (Fig. 10). With increasing temperature the wetting effect becomes less significant than the destruction or splitting of the droplet into several parts. Therefore, the combustion time of the droplet is practically the same as in the case of its motion perpendicularly to the surface.

Conclusions. The results of the experiments show that a fuel oil droplet (of diameter 2.3 mm) striking a hot surface passes through the same stages as a droplet freely moving in the space. However, the combustion of the formed carbon residue, whose calculated mass is less than 5%, constitutes more than 0.7 of the total lifetime of the droplet. Chromatograms have shown that under inert conditions the fuel oil transforms into a gaseous mixture of hydrocarbons — alkanes, alkenes, aromatic compounds. A high temperature promotes fast formation of a multitude of

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light hydrocarbons and heavy compounds. Products containing much carbon tend to polymerize to resins and coke, which burn up faster as the temperature is increased and a sufficient quantity of oxidizer is supplied. In other words, already at the onset of fuel oil combustion the temperature and the quantity of oxygen influence the process of solid residue formation from the gas phase. It has been established that the higher the heat conductivity of the wall, the faster the droplet burn up. Moreover, already at a temperature of 600°C on the rest of the surface the droplet "explosion" phase is reached. The surface roughness and a change in the droplet–wall contact angle promote the process of combustion only at temperatures below 550°C, and at temperatures above 550°C they do not increase the combustion rate of the droplet.

NOTATION

a, thermal diffusivity of the wall, m^2/sec; c, heat capacity of fuel, J/(kg·K); h, height, mm; s, step, mm; m, droplet mass, mg; t, time; sec; T, temperature, $^{\circ}$C; u, droplet velocity, m/sec; U, voltage, mV; x, y, coordinates, m; α, slope of the wall, deg; λ, heat conductivity of the wall, W/(m·K); ρ, fuel density, kg/m^3. Subscripts: v, volatile; coke, coke.

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