As a result of the experiments conducted, it has been found that practically all the investigated liquids disperse, provided that the appropriate conditions are observed, while the flow density and sizes of particles for liquids with low viscosity and high density are very small, which can restrict their practical usage. The application of the principle of superposition allows one to avoid this disadvantage. A high degree of dispersion, homogeneity of the constitution of particles, and negligibly small energy consumption of the technique provide for expanding the field of its practical application.

The electroconductive liquids disperse with more difficulty than the organic liquids with high specific resistances. The impurities of different organic liquids dissolving in water and solutions of salts improve the conditions of their dispersion. Thus, for example, small impurities of acetone and methyl alcohol in water and aqueous solutions of sodium chloride reduce the dispersion potentials by 27%.

NOTATION

d, inner diameter of the capillary; ρ, liquid density; η, coefficient of dynamic viscosity; σ, coefficient of the surface tension; U, capillary potential; G, liquid flow rate; ℓ, distance between electrodes; I, current between the electrodes; T_H, capillary temperature.

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HYSTERETETIC BEHAVIOR AND INERTIAL CHARACTERISTICS OF A FLAME OF DROPS OF HYDROCARBONS

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The results of an experimental investigation of the kinetics of the displacement of a flame, surrounding a drop of hydrocarbon fuel, accompanying an instantaneous change in the flow around the drop from zero to the detachment value are presented.

It is well known that when a burning drop is placed in a flow of oxidizer the thermophysical characteristics of the burning and the shape and size of the flame are closely related with the flow rate. When the flow rate is changed hysteretetic behavior of the flame surrounding a drop of hydrocarbon is observed; this behavior is associated with the existence of two critical velocities: The first one is determined by the maximum value of the flow rate for which the flame is located on any point of the drop and the second one characterizes the reestablishment of the flame on the bow point as the flame moves out of the wake of the drop [1].

The separation of a flame from burning drops has been studied in detail for stationary flow velocities. The reestablishment of the flame from the wake of the drop on the bow point

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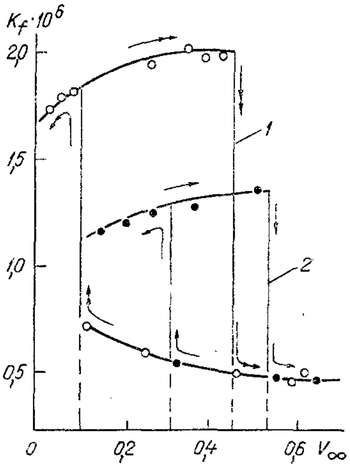

Fig. 1

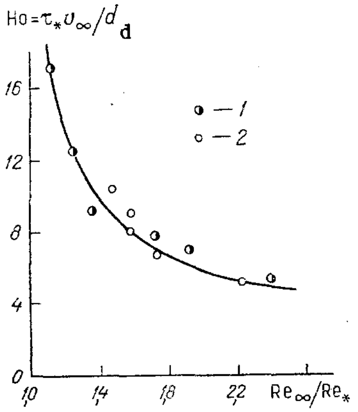

Fig. 2

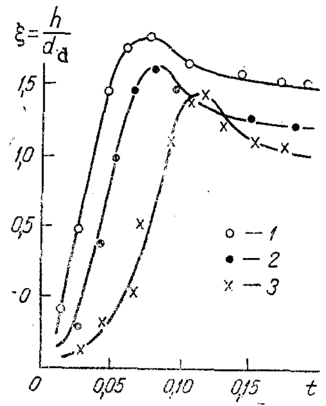

Fig. 3

Fig. 1. Rate constant for burning versus the flow velocity, $K_f = \varphi(V_\infty)$ (hysteresis): 1) ethanol; 2) acetone. K_f, m^2/sec; V_∞, m/sec.

Fig. 2. Effect of the dimensionless flow velocity on the extinguishment time of the flame: 1) ethanol; 2) acetone.

Fig. 3. Dimensionless coordinate of the flame $\xi = h/d_d$ as a function of time: 1) $V_{\infty 1}$ = 1.1 m/sec; 2) $V_{\infty 2}$ = 1.25; 3) $V_{\infty 3}$ = 1.5 m/sec. t, sec.

of the drop has not been studied in as great detail [2], and there are virtually no experimental works on the kinetics of extinguishment (detachment) for nonstationary rates of flow around the drop.

We investigated the displacement and extinguishment of a flame using the method of a porous sphere ("stationary drop") [2] in an air flow at room temperature and atmospheric pressure with drops of burning substances with strongly differing specific heats of vaporization. The displacement of the flame relative to the bow point of the drop, whose diameter varied (d_d = 3-9 mm), was determined with the help of motion picture photography and a photometric sensor, attached to a chronometer. The "stationary drop" was place at the cutoff of a Vitoshinskii nozzle, giving a square-shaped velocity profile. The critical velocity of the flow, the coordinate of the flame, and the rate constants of burning with stationary values of the flow velocities were determined. Measurements with an instantaneous change in the flow velocity were then performed. For this a small metal sphere 10 mm in diameter was placed in front of a stationary drop and a flow with velocity greater than the extinguishment velocity of the flame was supplied. The startup of the motion picture cameras and chronometers was synchronized with the removal of the small sphere from the center of the nozzle. The experiments, performed in the region $10 \leq Re_\infty \leq 300$, showed the following. Stationary values of the flow velocities ranging from zero to the detachment velocity V_* correspond to stationary positions of the flame and a stationary value of the rate constants for burning. As the flow velocity is increased $V_\infty > V_*$ the flame is displaced into the wake of the drop, and the rate constant of burning decreases. If after this the rate of flow is decreased, then the flame is reestablished on the bow point with a lower value of the flow velocity, i.e., $V_\infty = V_s < V_*$. This brings about a hysteretetic effect of the flow velocity on the rate constant for burning (Fig. 1); this effect is related with the temperature of the drop and the coordinate of the flame: $K_f = -(d/dt)(d_d^2)$.

When the flow velocity is changed instantaneously from zero $V_\infty = 0$ to $V_\infty > V_*$ the flame is extinguished at the bow point after a time τ_*, which decreases as the flow velocity is increased and increases when the diameter of the drop is increased (Fig. 2). The coordinate of the flame h, measured relative to the bow point of the drop, changes nonmonotonically with time: It reaches a maximum value and then decreases, after which it remains unchanged (Fig. 3). The process of reestablishment of the flame on the bow point of the drop lasts approximately three times longer than the process of extinguishment. After the flow is screened (the velocity drops to zero) the flame remains stationary for some time and then rapidly moves to the bow point and engulfs the drop. The velocity of the flame as it engulfs the drop is higher than at detachment.

Intense heat and mass transfer processes in the region of the hydrodynamic wake behind the drops play an important role in the reestablishment of the flame on the bow point as the velocity of the flow around the drop is instantaneously changed ($V_\infty \to 0$). A zone with circulation flow in the form of a stationary vortex ring forms in this region already for $Re_\infty \gtrsim 20$ [4]. The dynamic equilibrium of heat and mass transfer processes (the rate of vaporization dI/dt and the rate of liberation of heat dw_ν/dt) in the circulation zone creates conditions for establishing a flame front, determined by the parameters of burning, at a distance from the drop where the velocity of the flow equals the normal velocity of burning, i.e., $V_\infty = u_\nu$. If this relation is not satisfied, either the flame becomes detached ($V_\infty > V_*$) or it moves back to the bow point and engulfs the entire surface of the drop ($V_\infty \to 0$). This behavior of the flame agrees with the observed change in the pattern of circulation flow and the displacement of the position of the vortex itself with respect to the drop when one regime of flow around the drop is replaced by another [4]. The highest value of the number Re_∞ for which export of vorticity into the region of the external flow is still not observed, accoridng to the calculations of [5], is less than ≈ 300, which corresponds to the values achieved in the experiment. The process of extinguishment of the flame at the bow point of the drop for $V_\infty = V_*$ is associated with the fact that the maximum rate of evaporation and the corresponding maximum liberation of heat as a result of a chemical reaction in the stoichiometric mixture are achieved [3].

Since the surface of the flame in the vicinity of the bow point is spherical, by solving the equation of heat conduction in a spherical coordinate system

$$\frac{\partial}{\partial r}\left(4\pi r^2 \lambda \frac{\partial T}{\partial r}\right) + 4\pi r^2 w_\nu q = \frac{\partial}{\partial r}\left[I(V_*)\, c_p T\right] \quad (1)$$

with the boundary conditions $(\partial T/\partial r)(r_f, t) = 0$, $T(r_f, 0) = T_f$, $T(r_d, t < \tau_*) = T_s$, it is possible to determine, using Zel'dovich's method [3], it is possible to determine the detachment velocity of the flame as the maximum velocity of the flow at which the flame exists at the bow point of the drop. Integrating (1) over the range $r_d < r < r_f$, taking into account the fact that on the surface of the drop $\lambda 4\pi r^2 \partial T/\partial r(r = r_d) = IL$ and on the surface of the flame $\partial T/\partial r(r = r_f) = 0$, we obtain the condition

$$I(V_*)\left[L + c_p (T_f - T_s)\right] = \int_{r_d}^{r_f} q w_\nu 4\pi r^2 dr, \quad (2)$$

which determines the detachment velocity of the flame, when the maximum liberation of heat owing to the chemical reaction in the stoichiometric mixture [right side of the formula (2)] equals the maximum power required to evaporate liquid and heat the vapor from the temperature of the drop to the combustion temperature. For flow velocity $V_\infty > V_*$ Eq. (1) does not have a solution. It is obvious from Fig. 1 that for $V_\infty > V_*$ K_f decreases sharply; this decrease is associated with the extinguishment of the flame on the bow point of the drop and the displacement of the flame into the wake.

To find the right side of (2) we shall employ Zel'dovich's method, used in the theory of normal propagation of a flame in a premixed mixture. In the region $r_f - \Delta r < r < r_f$, taking into account the fact that $\Delta r / r_f \ll 1$ and $\partial T/\partial r \approx 0$, Eq. (1) assumes the form

$$\frac{\partial}{\partial r}\left(\lambda \frac{\partial T}{\partial r}\right) + q w_v = 0,$$

whence follows an expression for the density of the heat flux

$$4\pi r^2 \lambda \frac{\partial T}{\partial r}\bigg|_{r_f - \Delta r + 0} \approx 4\pi r_f^2 \sqrt{2q\lambda \int\limits_{T_f - \Delta T}^{T_f} w_v(T)\, dT}, \tag{3}$$

which is identical to the right side of (2).

In the "cold" region, close to the drop, $r_d < r < r_f - \Delta r$. Solving the heat-conduction equation (1)

$$4\pi \frac{\partial}{\partial r}\left(\lambda r^2 \frac{\partial T}{\partial r}\right) = \frac{\partial}{\partial r}\left[I(V_*) c_p T\right],$$

and neglecting the chemical sources of heat, we obtain

$$4\pi r^2 \lambda \frac{\partial T}{\partial r} = I(V_*)\left[L + c_p (T_f - T_s)\right]. \tag{4}$$

Then, integrating (4) with the boundary conditions $T(r = r_d) \approx T_s$, $T(r = r_f - \Delta r) \simeq T_f$, $(\Delta T / T_f \ll 1)$, we find an approximate formula for the mass rate of vaporization of the drop:

$$I(V_*) = \frac{\lambda}{c_p} 4\pi r_d \left(1 - \frac{r_d}{r_f}\right)^{-1} \ln\left[1 + \frac{c_p (T_f - T_s)}{L}\right],$$

which for the radius of the zone of combustion at the bow point [5]:

$$\frac{r_f}{r_d} = \left[1 - \frac{2}{\mathrm{Nu}(V_*)}\right]^{-1} \tag{5}$$

assumes the form

$$I(V_*) = \frac{2\pi r \lambda}{c_p} \mathrm{Nu}(V_*) \ln\left[1 + \frac{c_p (T_f - T_s)}{L}\right]. \tag{6}$$

It is convenient to give the dependence of the Nusselt number on the Reynolds number by the formula [6, 7]

$$\mathrm{Nu}(V_\infty) = 2 + 0{,}552\, \mathrm{Re}_\infty^{1/2} \mathrm{Pr}^{1/3} \simeq 2 + b\, \mathrm{Re}_\infty^{1/2} \tag{7}$$

and, in particular, $\mathrm{Nu}(V_*) \simeq 2 + b\,\mathrm{Re}^{0.5}$ ($\mathrm{Pr} = 0.71$), where $b = 0.54$.

From (4) there follows an expression for the density of the heat flux at the boundary $r = r_f - \Delta r$

$$4\pi r^2 \lambda \frac{\partial T}{\partial r}\bigg|_{r_f - \Delta r - 0} = I(V_*)\left[L + c_p (T_f - T_s)\right].$$

Using the condition that the heat flux is continuous

$$\frac{\partial T}{\partial r}\bigg|_{r_f - \Delta r - 0} = \frac{\partial T}{\partial r}\bigg|_{r_f - \Delta r + 0},$$

and the expressions (3) and (6), we obtain

$$I(V_*)\left[L + c_p (T_f - T_s)\right] = 4\pi r_f^2 \sqrt{2q\lambda \int\limits_{T_f - \Delta T}^{T_f} w_v(T)\, dT},$$

which is identical in physical meaning to (2). As follows from the theory of the normal propagation of a flame [3, 7]:

$$\sqrt{2q\lambda\int\limits_{T_f-\Delta T}^{T_f} w_v(T)\,dT} = \rho u_v c_p (T_f - T_s),$$

and then we obtain the condition for detachment of the flame close to that proposed by Spaulding [8]:

$$I(V_*)\,[L + c_p(T_f - T_s)] = 4\pi r_f^2\,\rho u_v c_p (T_f - T_s). \tag{8}$$

Substituting into (8) the expressions for $I(V_*)$ from (6) and $r_*(\mathrm{Nu}_*)$, and $\mathrm{Nu}(V_*)$, gives a condition for the detachment velocity of the flame

$$\mathrm{Re}_* = \frac{V_* d_d}{\nu(T)} \approx \left[\frac{Bd_d}{2b_*}\left(1 + \sqrt{1 + \frac{8}{Bd_d}}\right)\right]^2, \tag{9}$$

where $b_* = 2b$, since the heat transfer at the bow point is twice as intense than the average heat transfer over the entire surface of the drop,

$$B = u_v c_p (T_f - T_s)/a\,[L + c_p(T_f - T_s)]\ln\left[1 + \frac{c_p(T_f - T_s)}{L}\right].$$

For large values $Bd_d \gg 8$ Spaulding's condition for detachment is obtained [8]: $V_*/d_d =$ const, i.e., $V_*/d_d \neq f(d_d)$, and is determined by the thermophysical properties

$$\frac{V_*}{d_d} \approx \frac{\nu(T)}{b^2}\left(\frac{u_v}{a}\right)^2\left[\frac{B_f}{(1 + B_f)\ln(1 + B_f)}\right]^2, \tag{10}$$

where $B_f = c_p(T_f - T_s)/L$ is Spaulding's parameter.

For the drop sizes studied $Bd_d \simeq 1$, so that the calculation of V_*, performed using the formulas (9) and (10), gave results close to the experimental values with the maximum error not exceeding 15% with $b = 0.54$ and values of the transfer coefficients at the temperature $\langle T\rangle = (T_f + T_s)/2$.

When the flow velocity is changed instantaneously from zero to V_∞, greater than the stationary detachment velocity, the delay time of extinguishment τ_* of the flame at the bow point of the drop is determined by the decrease in the mass rate of vaporization $I(V_\infty)$ to the detachment value $I(V_*)$, which is related with the maximum liberation of heat as a result of chemical reaction in the stoichiometric mixture of fuel and oxidizer vapors. Then the extinguishment time can be determined approximately from the equation of heat balance

$$\tau_*\,[I(V_\infty) - I(V_*)]\,[L + c_p(T_f - T_s)] = \rho c_p (T_f - T_s)\,4\pi r_d^2 (r_{f_*} - r_d), \tag{11}$$

where

$$I(V_\infty) = \frac{2\pi r_d \lambda}{c_p}\mathrm{Nu}(V_\infty)\ln\left[1 + \frac{c_p(T_f - T_s)}{L}\right].$$

Substituting into (11) the expressions (5), (6), and (7) we can represent the dependence of the delay time for extinguishment of the flame at the bow point of the drop on the diameter of the drop, the velocity of the flow, and the thermophysical properties of the components in the generalized form

$$\mathrm{Ho} = \frac{\tau_* V_\infty}{d_d} = \frac{B_f}{(1 + B_f)\,b^2\ln[1 + B_f]}\left[1 - \sqrt{\frac{\mathrm{Re}_*}{\mathrm{Re}_\infty}}\right]^{-1}. \tag{12}$$

The formula (12) was employed to analyze the experimental results (see Fig. 2). Reynolds number, corresponding to detachment of the flame, was calculated using the formulas (9) and (10).

The extinguishment time decreases when the flow velocity V_∞ is increased and increases when the diameter of the drop is increased; this is confirmed by the experimental data. As the flow velocity approaches the detachment velocity the extinguishment time approaches infinity. The effect of the thermokinetic properties is taken into account by the parameter B_f and the Reynolds number Re.

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Thus, we have shown that flames surrounding a drop of hydrocarbons have inertia. It was found that the detachment velocity and the extingishment time of the flame are related with the drop diameter, the thermophysical properties of the drop, and the conditions of burning was determined.

NOTATION

V_*, V_∞, V_s, velocities of detachment of the flame, velocity of the flow, velocity of reestablishment of the flame, respectively; K_f, rate constant for burning; d_d, diameter of the drop; τ_*, extinguishment time of the flame; L, specific heat of vaporization; $I(V_*)$, mass rate of vaporization at the flow velocity V_*; c_p, a, λ, ν, and ρ, specific heat capacity, thermal diffusivity, thermal conductivity, kinematic viscosity, and density of the vapors of the gas mixture; w_ν, rate of the chemical reaction of the stoichiometric mixture; q, heat effect of the reaction; r_f, radius of the combustion zone; Δr, thickness of the combustion zone; u_ν, normal velocity of propagation of the flame; h, coordinate of the flame. Temperatures: T_a, T_f, T_s, and $\langle T\rangle = (T_f + T_s)/2$, adiabatic, burning, boiling, and average temperatures. Criteria: $Nu(V_*) = \lambda^{-1}\alpha d_d$, Nusselt's number; $Re_* = \nu^{-1}d_dV_*$, Reynolds number. Indices: *, detachment characteristics; f, burning; s, boiling; d, drop; ∞, flow. The brackets $\langle ... \rangle$ denote the average in the gas mixture in the combustion zone; B_f is the Spaulding parameter; Ho is the dimensionless extinguishment time.

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