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INFLUENCE OF A NON-UNIFORM ELECTRIC FIELD ON THE COMBUSTION OF LIQUID HYDROCARBON FUELS

The influence of a non-uniform electric fields (a cylindrical capacitor) on the combustion of liquid droplets of such hydrocarbons as benzene, hexane, and methanol, which are characterized by different soot formation degrees, is experimentally studied. It is shown that the applied field can both increase and decrease the fuel mass burning rate depending on the field polarity (direction) and the fuel type. The hysteresis phenomena – the flame lift-off from the droplet and the droplet coverage with flame – and their dependence on the field properties, are described.

Keywords: liquid fuels, soot formation, electric field, electric breakdown, mass burning rate.

1. Introduction

When studying the influence of the electric field on the combustion of hydrocarbon fuels, the consideration is confined, as a rule, to the case of uniform external fields [1–3]. Then, the main drop of the voltage occurs across the afterburning zone and exerts practically no effect on the combustion chemistry.

In work [4], it was found that the influence of the pulsing and dc electric fields on the reaction zone in the premixed "propane-air" flame depends on the applied voltage polarity. The majority of works on the electric field effect dealt with a diffusion flame. For instance, in work [5], the influence of the ion wind induced by an alternating high-frequency electric field on the stability of a gas-phase flame formed on the opposite fuel and oxidizer flows (diffusion flame) was studied theoretically. In work [6], a theoretical model of "ethylene-air" diffusion flame in the dc electric field was developed. The electric field was shown to affect the combustion rate and the combustion zone structure owing to its action on charged soot particles, i.e., via the electric wind.

The parameters of the diffusion flame on the opposite fuel (methane/nitrogen) and oxidizer (nitrogen/oxygen) flows in the ac electric field were experimentally studied in work [7]. It was shown that these parameters (the flame velocity and fluctuation) depend substantially on the ion wind, whereas the chemical and thermal field effects are practically absent. In work [8], electrical breakdowns in the plasma of a hydrogen-air flame were considered. The obtained results testify that negative ions make the main contribution to the ion wind. The interaction of the low-frequency electric field with the front of the premixed (methane-oxygen-nitrogen) flame, which results in quite powerful acoustic fluctuations of the flame front, was studied in work [9]. In work [10], an experimental study of the influence of a horizontal dc electric field on the burning rate and the structure of the diffusion flame was performed for stationary droplets of various hydrocarbon liquid fuels (hexane, benzene, and methanol). It was shown that the burning rate can increase by 15%, which is a result of the action of the ion wind mechanism on the flame shape and is associated with the growth of the heat and mass exchange between the droplet and the flame front. Similar results were obtained in work [11], where the evaporation and burning of non-stationary droplets in the vertical dc electric field were studied.

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When an external electric field is applied to a burning hydrocarbon fuel droplet, the directed motion of charged soot particles has to arise, which can be imagined as the droplet blowing by an external flow [12,13]. In work [14], it was shown that the convection enhances the burning rate by $1+U_\infty R/(2D_\infty)$ times, where U_∞ is the blowing flow velocity, and D_∞ is the diffusion coefficient of fuel in the oxidizing gas far from the droplet with the radius R. It was also shown that, depending on the blowing flow, the relative mass burning rate (MBR), K/K_0-1, can be approximated as Re/2, where Re is the Reynolds number, with the experimental points for heptane and methanol satisfying this relation quite accurately [10].

From our viewpoint, it would be more effective to apply a field that "pierces" the flame, i.e., affects the preparation zone located immediately in front of the flame. In this paper, in order to determine how non-uniform electric fields affect the parameters of a diffusion flame, we studied the influence of such fields with the pre-breakdown and breakdown magnitudes on all flame zones (the preparation and combustion zones, and the zone of combustion products). The object of research was the flame formed on stationary droplets of liquid hydrocarbon fuels (methanol, hexane, and benzene) [12]. The choice of those fuels was associated with different degrees of soot formation at their burning in air. In particular, benzene forms a lot of soot at its burning. At the same time, the burning of hexane is characterized by a moderate soot formation. Finally, when methanol is burned, no soot is practically formed; therefore, no appreciable effect is observed for it in a uniform field [10].

2. Experimental Setup and Research Methods

The experiments were carried out using the stationary droplet method [10]. A stationary droplet of a liquid fuel 3–10 mm in diameter was modeled as a porous ball fabricated from a thin metal net and impregnated with fuel. The fuel was evenly and continuously supplied into the ball through a thin needle with the help of an electromechanical batcher. In the course of stationary combustion, we sought for such a fuel consumption, at which the ball was covered with a uniform liquid layer of a permanent thickness. This method makes it possible to achieve the maximum stationarity of the combustion process.

A non-uniform field was created by applying a high dc voltage to a cylinder 80 mm in diameter made of a metal net and to the ball located at the center of this cylinder. Experiments were also performed with a metal ring of the same diameter. In this case, the ball was located on the ring axis. In the course of the experiment, the distance from the ball to the ring plane changed. The electric current flowing through the system was registered by means of an oscilloscope. Burning droplets were also photo- and video-registered.

Every time, the data for the droplet burning in the field were compared with the data obtained in the burning absence. This method allowed the influence of the field on the mass burning rate to be fixed with an accuracy not exceeding 3%.

3. Experimental Results

In the case where a positive potential (+) is applied to the droplet, and a negative (−) one to the net, the flame is attracted to the external electrode. This occurs for the same reason as in the case of uniform field [10], i.e., due to the action of the ion wind mechanism. In this case, the flame acquires a shape of a bell with the open end directed upward, because soot particles, which are positively charged due to the thermal emission, are attracted to the negatively charged net, and they capture the gaseous medium at that. As the field strength increases, the flame top becomes more and more open (the flame is absent at all from a substantial part of the surface). As a result, the average distance from the droplet to the combustion zone, as well as the fraction of the surface on which the reaction does not take place, increases, and the heat flow from the combustion zone to the droplet decreases. Therefore the MBR decreases (see Fig. 1) in full accordance with the assumption about the mechanism of the field influence on the combustion process via the ion wind. (For a comparison, we note that if a uniform field is applied [10], the mass velocity always increases as a result of the electric wind effect.) In Fig. 1, $\dot{m}$ is the mass burning rate, when the field is switched-on, $\dot{m}_0 = 0.069$ kg/m^{2}s is the mass burning rate in the field absence, and the droplet diameter equals 5.6 mm. At $U > 5$ kV, the experimental results can be ambiguous, because the flame symmetry is randomly violated and, similarly to the burning in a uniform field, the flame can be attracted in whole to the negative electrode. The flame velocity can increase at that, If the field polarity is opposite ("–" at the droplet and "+" at the cylindrical electrode), the flame, on the contrary, is attracted to the droplet, because the positively charged soot particles are now attracted to the negatively charged sphere, thus intensifying the heat transfer to the droplet surface, which is responsible for the increase of the burning rate. At a voltage exceeding 2 kV, an electrical breakdown through the flame is observed.

For methanol, the following features were experimentally observed (see Fig. 2). First, the MBR does not depend on the field polarity in the non-uniform electric field, as opposed to the uniform-field case. In other words, if soot particles are almost absent, the electric wind mechanism does not manifest itself, and the field affects only the chemistry of running reactions. In both cases, a reduction of the MBR took place.

When the field strength reaches a breakdown magnitude (irrespective of the polarity and shape of the external electrode; this can be a needle, a plate, a ring, or an electrode of other shapes), there arises a chaotic sequence of spark discharges between the droplet and the electrode, which is accompanied by the appearance of a strong flame turbulization. The mass burning rate increases 2–4 times. Such a growth can be a result of both the kinetic mechanism (because the spark channels that "pierce" the combustion and fuel preparation zones are powerful sources of supplying chemically active particles into the reaction zone) and the turbulization of the combustion zone.

4. Non-stationary Electric Field and Hysteresis Phenomenon

The experiments described above were carried out in the stationary (i.e., permanent) non-uniform field. The experiments in the non-stationary non-uniform field ("+" at the droplet and "–" at the net) showed that the flame firstly began to oscillate chaotically as a whole, if the field strength increased. As the voltage grew further, the flame shape transformed into a strongly elongated "tail" that extended from the droplet to the metal net. At higher voltages, the upper part of the flame approached closer to the droplet. Then, at the voltage $U_{\rm cr}^{\rm lif}$, a sudden flame liftoff and its passage into the zone located behind the droplet took place. If, afterward, the voltage between the capacitor's covers decreased, the droplet became completely covered with fire. This process took place as drastically as the previous flame liftoff, but, unlike the latter, at a lower voltage, $U_{\rm cr}^{\rm cov}$.

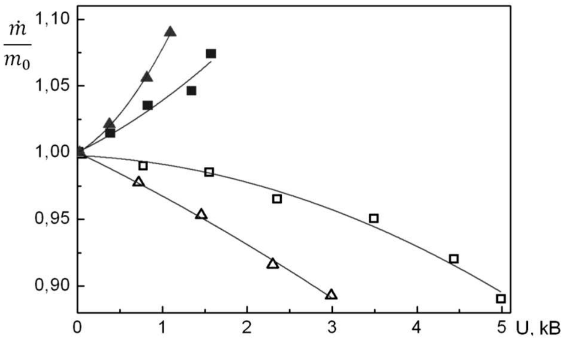

Fig. 1. Influence of a non-uniform cylindrical electric field on the burning rates of hexane and benzene for various field polarities; "+" at the droplet: hexane (■), benzene (▲); "–" at the droplet: hexane (□), benzene (△)

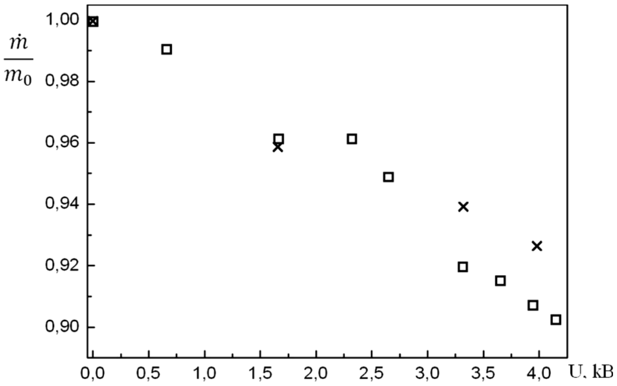

Fig. 2. Dependence of MBR on the non-uniform field magnitude for methanol for various droplet polarities: "+" at the droplet (□), "–" at the droplet (×). d = 5.6 mm, $\dot m_0$ = = 0.078 kg/(m^{2}s)

Figure 3 illustrates the dependences of the lower limit of the flame front, z/d_k, in the non-uniform cylindrical field on the applied voltage for hexane (panel *a*), methanol (panel *b*), and benzene (panel *c*). Let us consider the researched process in more details. As one can see from Fig. 3 *a, b, c*, at the voltages between the capacitor plates $U < U_{\rm cr}^{\rm lif}$, the flame coordinate with respect to the droplet center remains practically invariant. As the voltage slightly exceeds $U = U_{\rm cr}^{\rm lif}$, the flame coordinate drastically changes, and the flame liftoff takes place into the zone behind the droplet. If the voltage decrease afterward and reaches values $U < U_{\rm cr}^{\rm cov}$, the flame becomes restored at the frontal point at its motion from the zone

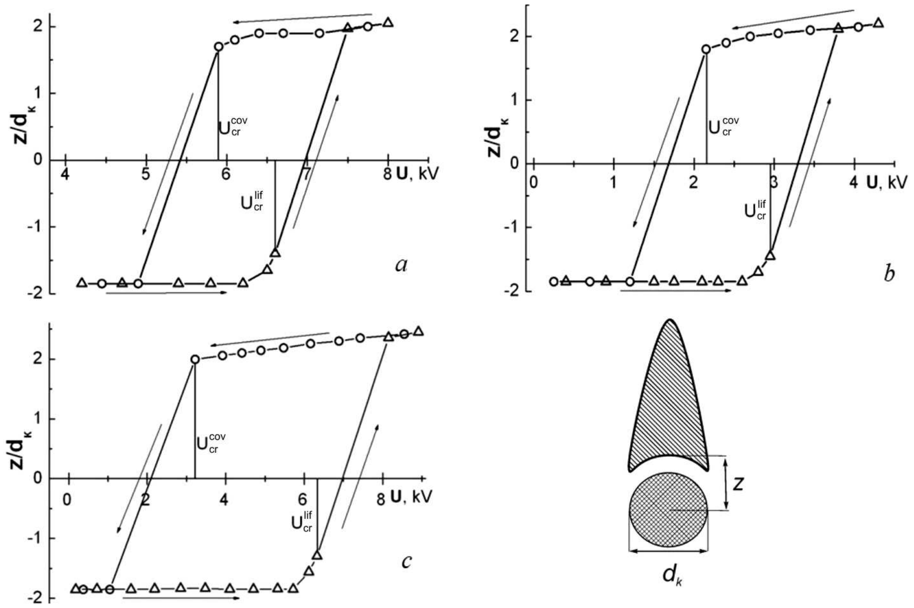

Fig. 3. Dependences $z/d_k(U)$ for the non-uniform cylindrical field: coverage (○), liftoff (△). $d_k = 5.6$ mm. methanol, $\dot{m}_0 = 0.078$ kg/(m^{2}s), $\dot{m} = 0.034$ kg/(m^{2}s) (*a*); hexane, $\dot{m}_0 = 0.069$ kg/(m^{2}s), $\dot{m} = 0.049$ kg/(m^{2}s) (*b*); benzene, $\dot{m}_0 = 0.031$ kg/(m^{2}s), $\dot{m} = 0.012$ kg/(m^{2}s) (*c*)

behind the droplet. The critical voltages of the flame liftoff from the droplet, $U_{\rm cr}^{\rm lif}$, and the droplet coverage with flame, $U_{\rm cr}^{\rm cov}$, as well as the area of the hysteresis loop change depending on the examined fuel, which can be seen from Fig. 3.

A similar phenomenon was studied in work [12], where a hysteretic behavior of the flame, when the droplet was blown by a convective flow, was described. In particular, acetone and alcohol droplets were researched. In work [13], where it was shown that the critical blowing velocity for a burning droplet, $V_{\rm zr}$, at which the flame liftoff takes place equals 27–58 cm/s. We proceed from the assumption that the flame liftoff occurs, when the velocity of the electric wind induced by the corona discharge between the outer capacitor cover and the flame becomes comparable with the velocity of the Stefan flow of combustion products flowing out from the combustion zone to the outside. In this case, a hypothesis can be put forward that the electric wind velocity at the flame liftoff moment should correspond to the critical velocity of the hydrodynamic flow that blows round the droplet, $V_{\rm lif}$.

Let us evaluate the characteristic velocity of the Stefan flow for the lower part of the flame, because the flame liftoff starts from the frontal point of the ball. It can be shown that the velocity of the Stefan flow of combustion products equals

$$V_{\rm st}^{\rm prod} = \frac{\dot{m}}{\rho_g}\frac{r_{\rm k}^2}{r_{\rm f}^2}\frac{T_{\rm pr}}{T_0}\frac{n_{\rm pr}}{n_0},$$

where $r_{\rm f}$ is the radius of the combustion zone (its front); n_0 and $n_{\rm pr}$ are the numbers of moles of the initial substance and the combustion products, respectively; and T_0 and $T_{\rm pr}$ are their respective temperatures. In particular, for hexane, $V_{\rm st}^{\rm prod} \approx 15$ cm/s. If the velocity of the convective flow blowing round the droplet is larger than the velocity of the Stefan flow, i.e., $V_r > V_{\rm st}^{\rm prod}$, the flame liftoff takes place. Hence, the flame liftoff from a droplet burning in an electric field has a hydrodynamic character, but, unlike the convective liftoff, it is governed by the mechanism of the electric wind generated by the corona discharge.

5. Conclusions

The main results obtained in this work can be summarized as follows.

It is experimentally shown that the mass burning rate for liquid hydrocarbon fuels (gasoline, benzene, hexane *etc.*) can be both increased and decreased (up to 15%) by applying external non-uniform electric fields with various configurations and magnitudes below the breakdown value. It is found that, in the case of the flame with soot particles, this effect arises due to the ion wind mechanism, namely, as the result of the motion of charged soot particles in the field. For the sootless flame (methanol), the mass burning rate decreases for any field polarity, which may probably occur due to the field effect on the chemistry of reactions in the pre-combustion and combustion zones. When reaching the breakdown voltage values, the mass burning rate can increase 2–4 times.

It Is shown that, in the case of non-uniform electric field below the breakdown value, the processes of flame liftoff from the droplet or the droplet coverage with flame has a hysteretic character at the critical burning rate, which is lower than the stationary one, for any type of hydrocarbon fuel. Unlike the convective flame liftoff, the origin of this phenomenon is associated with the electric wind mechanism. The electric wind velocity in the non-uniform electric field is comparable to the critical velocity of the flame liftoff by the hydrodynamic flow blowing round the flame.

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ВПЛИВ НЕОДНОРІДНОГО ЕЛЕКТРИЧНОГО ПОЛЯ НА ГОРІННЯ РІДИННОГО ВУГЛЕВОДНЕВОГО ПАЛИВА

Експериментально досліджено вплив неоднорідного електричного поля (циліндричний конденсатор) на горіння вуглеводневої краплі бензолу, гексану, або метанолу, для яких притаманний різний ступінь утворення сажі. Показано можливість як збільшення, так і зменшення масової швидкості горіння в залежності від полярності (напрямку) поля і виду палива. Описано гістерезисні явища у процесі зриву або охоплення краплі полум'ям в залежності від величини поля.

Ключові слова: рідинне паливо, сажоутворення, електричне поле, електричний пробій, масова швидкість горіння.