ROLE OF CHARGED SOOT GRAINS IN COMBUSTION OF LIQUID HYDROCARBON FUELS IN EXTERNAL ELECTRIC FIELD

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UDC 536.46

We consider the possibility to influence the process of combustion of liquid hydrocarbon fuels by applying an external electric field. The investigations were made for the typical representatives of fuels depending of the soot production rate. The mechanisms of influence of electric fields on the processes of combustion are considered, and it is shown that the mechanism of ion wind, through charged soot grains that are formed in flame, is dominant. Measurements of the flame front temperature are made.

Introduction

At present, the use of the combustion processes for energy achievement, i.e. the burning of various types of fuels, plays an important role in power, transport, metallurgical, and other branches of industry. So, 70% of the total energy produced now in the world are obtained from the combustion of organic fuels. In spite of the appearance of such complex problems like the exhaustion of natural resources and the deterioration of the ecological situation on the Earth due to the contamination of the atmosphere by the products of incomplete combustion, the situation will not change noticeably in the nearest future according to the prognoses of specialists [1, 2].

Thereby, the efforts directed to searching for parameters that will allow one to optimize the processes of combustion are actual [1, 3—8]. It is also necessary to account the interphase interactions [9]. Therefore, along with the traditional means of the control over and managing of combustion processes (such as the gas-disperse and chemical ones), the so-called non-traditional methods (the electrophysical ones, for instance) are also worked around now [10, 11].

On the basis of the investigations of particularities of the influence of electric fields on the process of combustion, it is possible to create new ways of the managing of combustion processes in power and technological installations. This will provide lowering the fuel consumption, decrease in the pollution of the environment and atmosphere, intensification of combustion processes on the one hand, and increase in the efficiency of the means of fire- and explosion safety and decrease in the consumption of fire-fighting means on the other hand.

Below, we will investigate the behavior of flame in a uniform electric field that is imposed integrally to it.

1. Mechanisms of Influence of External Electric Field on the Flame of Liquid Hydrocarbon Fuels

Electric properties of a flame are conditioned by the existence of charged particles, ions and electrons, in it. In 1928, J.J. Thomson advanced a hypothesis about the leading role of electrons in the flame spreading; it is an object of discussions up to now.

The specificity of the electric phenomena of combustion that differs it from the classical objects of investigation in a low-temperature plasma is the following. When a flame is placed in the electric field, charged areas appear and the redistribution of the potential of the applied field takes place due to diffusion of ambipolar carriers of charge.

The sources of charged particles in flame are spatially distributed chemical reactions. These chemoionization reactions are the cause of main particularities of the ionization structure of a flame front.

It is experimentally established that a flame is characterized by a spatial distribution of charges [12, 13]. A positive volume charge is concentrated in the reaction zone and the negative one is located in the pre-flame zone, i.e. in the area of preparation. It should be noted that electrons and negative ions are the carriers of negative charge in flame. In addition, experimentally stated are the next facts:

transverse extent of the flame front under normal conditions is less than one millimeter;

concentration of charged particles exceeds significantly (by several orders) the thermodynamically equilibrium value;

thermodynamic electron-ion equilibrium is obtained at a significant (in comparison to the transverse extent of the flame front) distance [14].

The foresaid shows that one can speak about the natural (characteristic of the nature of the flame front structure) and artificial (caused by external causes) distribution of charges in flame. In these cases, one can speak about the 'own' electric field of flame and an external field, respectively. The distribution of charges in an external field is a cause for the appearance of mass forces that affect a neutral gas from the side of the electric field. These forces cause the corresponding redistribution of gasodynamical parameters of a flux and, as a consequence, changes in the area of the flame envelope, flame spreading speed, its hydrodynamic stability, stabilization conditions, heat-mass transfer to a solid wall, concentration of formed carbon, etc. These mass forces may be by two-three orders larger than the gravitational force.

Attempts to investigate a structure of the own electric field of a hydrocarbon flame were made in [15], where a passive, without applying any external e.m.f., electric probe was the source of information about the field configuration.

'Own' electrogasodynamic effects appear due to different mobilities of ions and electrons, which leads to the diffusive distribution of charges and to the formation of an internal electric field inside the flame.

The electric field is distributed unevenly in a gap between electrodes. For instance, if there is a plane flame front situated between plane electrodes, then the field consists of three areas different by their nature: the flame front, area with the prevalence of negative charge, and area with the prevalence of positive charge. The main fall of voltage takes place in the last area due to a low mobility of heavy ions.

The asymmetry of the electric field means the inequality of electric forces acting towards the positively and negatively charged electrodes. Although sizes of the zones with positive and negative charges are equal, the forces that act on the former of them towards the negative electrode are prevalent. Variations in the gasodynamic characteristics in this area exceed those in other areas. That is, when the field is switched on, there appears the effect of 'electric wind', i.e. the directed motion of charged grains (of soot or oxide) along the force lines of the field. These grains can carry away a gas and change a regime of its flow. This leads to changes in the form of the flame, its distribution speed, and mass combustion rate. The mechanism of ion wind is usually realized when a field is applied integrally to the whole zone of flame. In such a case, the field doesn't penetrate into the zones of combustion (when the external field is uniform, for instance, the field of a plane capacitor), or this mechanism dominates as compared to the mechanism of a kinetic influence (while the field intensity is less than a shot-up value).

Along with the electrogasdynamic mechanism of influence on flame, we can consider the thermal (the dissipation of electric energy into thermal one) and kinetic (related to a direct influence of the field on the kinetics of chemical reactions) mechanisms. The estimates show that the former is negligible and the latter may take place when the field is applied locally to the fuel preparation zone (the pre-flame zone), if it is possible technically, for instance, in case of a gas-phase flame of the Bunsen type.

The distribution of the own electric field intensity for the high and low ionization rates was investigated in [16, 17]. It was shown that the maximal intensity of the own electric field is 10–50 V/cm for hydrocarbon flames with concentrations of ions of about 10^{12} cm^{-3}.

So, it can be stated that an electric field, being applied to a burning object, is an effective channel for the managing of combustion.

Almost all works state a strong influence of an electrical field on the combustion characteristics. The grade of such an influence achieves the maximum when the diffusive combustion takes place.

A direction of the electric field relative to the direction of lines of the flame flow (usually one says about longitudal and transverse electric fields) influences essentially the observed effects, as well as the polarity of electrodes that produce a field in the space between them. The last one is due to the mobilities of charge carriers of opposite signs in flame that may vary extremely strongly under different conditions.

It was supposed that a combustible mixture is prepared to the entering into the reaction due to electrons and ions that appear in the flame front. Consequently, charged grains define the flame propagation process.

The conception of the influence of an electric field on combustion through the mechanism of ion wind is based upon some basic considerations. A mechanical movement of a gas due to the 'ion wind' can change the flame propagation speed, while the normal speed of combustion is not changed. Since flame is an electrical system with distributed space charge, the applying of a field leads to a change in the form and area of the flame envelope. The last one changes the general combustion rate and, as a result, the flame propagation speed. A change of the flame front curvature in a field caused by a casual change of the mobility of charge carriers changes the normal combustion speed. It increases if the flame front is turned by concavity to the mixture that hasn't reacted yet and decreases if the flame front is turned to it by convexity. It can be explained by keeping in mind that radicals have different heat-transfer and diffusion characteristics in curved flame fronts [11].

The stationary drop method is one of the most convenient ones for studying the combustion of liquid hydrocarbon fuels from the viewpoint of both the determination of the mass combustion rate and the investigation of the active influence of an electric field on the process of combustion.

An aim of this work is the determination of a degree of influence of an electric field on the stationary combustion of drops of liquid hydrocarbon fuels burning between the plates of a plane capacitor.

2. Experimental Technique and Method of Investigations

Here, we present the results of experimental studies of the influence of an electric field on the combustion of drops of liquid hydrocarbon fuels burning between the plates of a plane capacitor, in particular, on a structure of the combustion zone, mass combustion rate, and its convective instability achieved for a stationary drop for a wide range of liquid hydrocarbon fuels (such as methanol, hexane, benzene, etc.). This procedure used allows carrying the investigations under well-controlled conditions that can be easily varied.

The investigations were carried out within the stationary drop scheme. A stationary drop of liquid fuel from 3 to 10 mm in diameter was formed on a porous spherical particle made of a fine metal mesh. Fuel was supplied evenly through a thin (1 mm in diameter) needle with the use of an electromechanical supplier, the speed of supply being controlled by an electronic voltmeter. During the process of stationary combustion, it was necessary to achieve such a consumption of a fuel when the drop is covered with a thin liquid layer of constant thickness. The control over the thickness was performed with a visual tube. Such a procedure allows achieving the maximal stationarity of combustion. We also investigated the influence of a field on the burning-out time of fuel from the porous sphere.

The high-voltage block was fed from a rectifier producing a constant high voltage that can be varied from 0 to 10 kV. It was applied to the plates of a plane capacitor of 0.1 m in width and 0.15 m in height. The information about the current that runs through the capacitor was obtained by using an oscilloscope that measured the difference of capacitor plates' potentials. Moreover, we performed the photo- and video-registration of the burning drop. Every time data about combustion in the field were matched with those without field. Such differential method allows noticing the influence of the field on the mass combustion rate with a precision of $\leq 3\%$.

Base data on the specific (per unit of the drop area) mass combustion rate with the field switched-off are given in Table 1.

In the diffusion regime of combustion, the mass combustion rate from the entire area of a drop is defined by the expression $\overset{\bullet}{M}=4\pi r^2\beta C_\infty \upsilon_{\mathrm{st}}$, where C_∞ is the oxidizer concentration in the surrounding ambience, υ_{st} is the stoichiometric coefficient in the oxidizer reaction, and $\beta = NuD/2r$ is the mass-heat-transfer coefficient. Thereby, $\overset{\bullet}{M} = 2\pi r NuDC_\infty \upsilon_{\mathrm{st}}$, or $\overset{\bullet}{M}/r = 2\pi NuDC_\infty \upsilon_{\mathrm{st}}=\mathrm{const}$.

In the diffusion regime of combustion, the mass combustion rate under the burning-out of fuel must be proportional to the radius of a drop.

There exists a limited range of drop sizes, for which the Sreznevsky law is confirmed experimentally. So, for particles with $r \geq 2.7$ mm, a significant deviation from $\overset{\bullet}{M}/r$ = const is observed, which is probably due to increasing the role of natural convection along with increase in the drop size. It is known that, under

Table 1. Mass combustion rate of hydrocarbon fuels

Fuel	Chemical formula	$\overset{\bullet}{m}_0$, kg/(m^{2}s)
Pentane	C_5H_{12}	0,095
Benzene*	C_6H_6	0.067
Hexane	C_6H_{14}	0.069
Toluene	C_7H_8	0.054
Heptane	C_7H_{16}	0.052
n-xylole	C_8H_{10}	0.050
Octane	C_8H_{18}	0.050
Methanol+	CH_4O	0.034
Ethanol	C_2H_6O	0.037
Acetone	C_3H_6O	0.052
1-butane	$C_4H_{10}O$	0.034
Dioxane	$C_4H_8O_2$	0.060
1-penthanol	$C_5H_{12}O$	0.042
Benzyl alcohol*	C_7H_8O	0.030

* combustion is accompanied with the powerful smoking,

\+ smoking is almost absent.

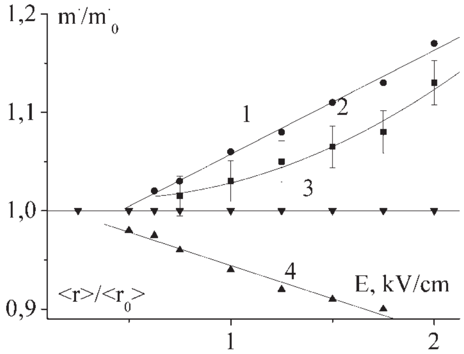

Fig. 1. Dependence of the relative mass combustion rate $\overset{\bullet}{m}/\overset{\bullet}{m}_0$ for benzene (*1*), hexane (*2*), and methanol (*3*) and relative radius of the combustion zone $\langle r\rangle/\langle r_0\rangle$ for hexane (*4*) on the electric field intensity

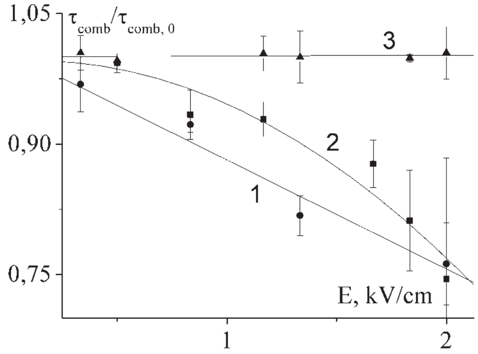

Fig. 2. Dependence of the relative fuel burning-out time on the intensity of a stationary uniform electric field: *1* — benzene, *2* — hexane, *3* — methanol

conditions of the developed convection, a correlation $\overset{\bullet}{M} = \beta r^{3/2}$ must take place.

In the present work, we used a range of drop sizes, where the diffusion regime of combustion is realized. Otherwise, at switching on the field, the badly controlled effects related to the uncertainty of a relative role of convection and the field may appear.

The experiments were carried out mainly with methyl alcohol, hexane, and benzene (benzine). Such a choice is conditioned by the fact that methyl alcohol burns practically without smoke, whereas the burning of hexane and benzene is accompanied, respectively, with moderate and powerful formation of soot. Other materials reveal the same qualitative features as three afore-mentioned ones.

3. Results of Experiments

When the field is switched off, the flame front is extended very strongly in the vertical direction due to gravitational convection; the ratio of the flame height to its diameter is from 6 to 8. When the field is applied, the flame front regardless of the used fuel bends to the negatively charged plate of the capacitor. The rate of this bend increases with the field intensity and reveals itself stronger for a powerfully smoking flame. Methanol is an exception since it doesn't practically react to the presence of the field. Sometimes methanol occasionally didn't burn completely (it was seen by a change of blue color to yellow one, and soot arose), and this can be observed: the flame began to bend to the negative electrode in this case.

The dependence of the relative mass combustion rate (the ratio of combustion rate with the field switched-on $\overset{\bullet}{m}$ to that without field $\overset{\bullet}{m}_0$, i.e. value $\overset{\bullet}{m}/\overset{\bullet}{m}_0$) on the field intensity (for voltages less than the shot-up one) is shown in Fig. 1. The effect of the field reveals itself stronger for a smoking fuel. All the above-presented testifies to the defining role of soot grains formed in flame.

Concerning the mechanism of this influence, we can state that the flame envelope constantly varies during a process of combustion (see below). However, on the average, the distance from a drop to the flame front decreases while the field increases (Fig. 1). In order to determine the average distance $\langle r\rangle$, all the surface of the flame was divided into zones that can be seen at the same angle from the particle center, and $\langle r\rangle$ was determined as

$$\frac{1}{\langle r\rangle} = \sum_i \frac{\cos\gamma_i}{r_i},$$

where $\langle r_0\rangle$ is the average distance without field.

It is experimentally stated that the fuel burning-out time from the porous sphere decreases with increase in the electric field intensity [18], while the mass combustion rate increases. The experiments were made for hexane, benzene, and methanol.

So, it was stated that increasing the mass combustion rate (up to 15% in the case of benzene) is a result of approaching the surface of the combustion zone as a whole to the drop, which leads to the intensification of heat-mass change between the flame front and the drop.

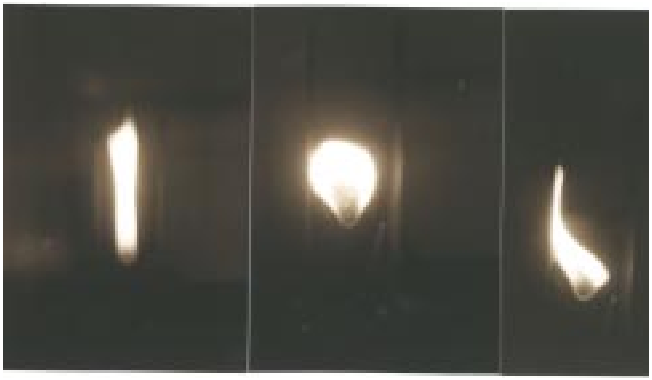

Fig. 3. General view of flame in an electric field, left to right: without field, with a field of 0.5 kV/cm, with a field of 1.5 kV/cm

The mass vaporization rate of a liquid fuel increases during this process.

The experiments that were carried out testify to that the ion wind is responsible for the transformation of the reaction surface. The ion wind is realized due to the movement of positively charged grains of soot (their charging is a result of the thermoelectric emission in flame), which are the most massive and the least mobile from all charged components of flame, in the electric field.

3.1. Instability of a Drop Combustion Process

In all the cases of the hydrocarbon drop combustion, the current running through the capacitor varied periodically (Table 2). The periods of current oscillations are close by their values, and a sort of fuel influence them weakly (and there is no clear correlation between the mass combustion rate and the period). The experiments were carried out under changes in various parameters of the system: U (under L=const), L (under U=const); and both U and L (under $E = U/L$=const). The experiments showed that the period can be changed almost twice, but the qualitative particularities of the process remained unchanged. The video recording showed that the form of flame changed synchronically. At small electric fields when flame doesn't touch the negative electrode, the form of flame is changed during the period of oscillations from a practically spherical to elongated one towards the electrode. While touching an electrode (in the case of large electric fields), the flame periodically 'flows' along the electrode in the vertical direction (Fig. 3).

Table 2. Periods of current oscillations ($d = 6.6$ mm, $U = 2.9$ kV, $L = 50$ mm)

Fuel	Hexane	Heptane	Pentane	Butanol	Octane
T, s	0.085	0.1	0.11	0.1	0.1
Fuel	Acetone	Benzene	Benzyl alc	Toluene	Benzine(A-80)
T, s	0.08	0.1	0.08	0.13	0.09

The amplitude of the current during this process increases with the electric field intensity E. If the field was non-uniform, the same periodic changes of the current and the form of the flame surface took place.

The above-presented allows us to assume that the convective instability of the products of combustion of a hydrocarbon drop is responsible for these oscillations. Actually, the special investigations carried out with needle electrodes located in the product zone under low voltage (that didn't influence the combustion process) showed the existence of these autooscillations with the field switched-off. Moreover, the video recording of the flame of the drop with the field switched-off has revealed a periodic bending of the flame front in its upper part with a period that corresponds to the period of current oscillations during the combustion with the field switched-on. This transformation is probably conditioned by the periodic appearance and take-off of curls in the zone of combustion products. The qualitative picture is analogous to that of the convective instability of flame propagating in slowly burning mixtures, when flame is propagating along the vector of gravity force.

Here, we present some estimations of the gravitational instability of the combustion of a hydrocarbon drop. It is known that the effect of gravitational convection can be significant when $v^2/gd_{\text{f}1} \leq 1$, where $g = 9.8$ m/s^2 — acceleration of free fall, $d_{\text{f}1}$ — diameter of the combustion zone, v — speed of the Stefan flux of combustion products. Under conditions of our experiments, $v_{\text{cr}} \approx 0.11$ m/s for hexane. In our experiments,

$$\bar{v} = \frac{2\overset{\bullet}{M}}{\pi d_{\text{f}1}^2 \rho_p}\varepsilon\frac{d_{\text{f}1}}{l} = 1.5 \times 10^{-2}\,\text{m/s}.$$

Here, $\overset{\bullet}{M}$ is the mass combustion rate of the total drop surface,

$$\varepsilon = \frac{T_{\text{f}1}}{T_0}\frac{n_{pr}}{n_0}$$

is the degree of thermal expansion of combustion products ($T_{\text{f}1}$ is the combustion temperature found to be equal to $T_{\text{f}1} = 1720$ K for hexane [19]; T_0 is the initial temperature, and n_{pr} and n_0 are the quantities of moles that appear and enter into the reaction, respectively). Under identical conditions, the speed of the convective flow $v_c \cong \sqrt{d_{\text{f}1}g} \cong 0.35$ m/s. Thereby, $\bar{v} < v_c$, and the role of convection is significant in the products of combustion.

The characteristic convection development time

$$\tau_* = \frac{\mathrm{Ra}^{2/3}\mathrm{Pr}^{1/3}\mathrm{Re}^{-1/3}}{2^{2/3}\pi\left(\frac{\varepsilon-1}{\varepsilon}\right)^{2/3}},$$

where $\mathrm{Ra} \approx 10^3$ is the Rayleigh number, $\mathrm{Re} \approx 280$ is the Reynolds number, and $\mathrm{Pr} \approx 1$ is the Prandtl number.

Then the period of oscillations that are conditioned by the periodic appearance and take-off of convective curls in the zone of combustion products $T = \tau_* \sqrt{d_{\mathrm{fl}}/g} \approx 0.1$ s that coincides with the experimentally obtained value.

Thus, the periodicity of the current is really conditioned by the convective instability of the combustion zone: convective curls carry, at the same time, the electric charge. Also, the special investigations (fast video-recording) have revealed that the periodic changes of the flame form take place with the switched-off field as well. The electric field allows showing that effect by using periodic current changes.

Conclusions

The main results derived in the work may be summarized as follows.

1. We have developed a method for the investigation of main electrophysical characteristics of liquid hydrocarbon fuels that is based on applying the external electric field of a definite configuration.

2. It is shown that a burning liquid particle consists of a low-temperature plasma with the condensed disperse phase (soot grains for hydrocarbon fuels). The charged state of the system plays an essential role in the processes of condensation and formation of soot.

3. As proved experimentally, it is possible to increase a mass combustion rate for liquid hydrocarbon fuels (benzine, benzene, hexane, etc.) up to 15% by applying an external electric field of definite intensity and configuration. It is stated that this influence is due to the mechanism of ion wind as a result of the movement of charged soot grains in the field that leads to a transformation of the flame envelope.

4. The autooscillatory regime of combustion of a drop, that is due to gravitational convection in the products of combustion, is investigated. This effect also reveals itself in a periodic change of the electrical current through the capacitor containing a burning object.

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РОЛЬ ЗАРЯДЖЕНИХ ЧАСТИНОК САЖІ У ПРОЦЕСІ ГОРІННІ РІДКОГО ВУГЛЕВОДНЕВОГО ПАЛЬНОГО У ЗОВНІШНЬОМУ ЕЛЕКТРИЧНОМУ ПОЛІ

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Резюме

Розглянуто можливість впливати на процес горіння рідких вуглеводневих пальних шляхом накладання зовнішнього електричного поля. Дослідження проведено для типових видів пального у залежності від ступеня сажоутворення. Розглянуто механізми впливу електричного поля на процеси горіння, показано, що домінуючим є механізм іонного вітру крізь заряджені частинки сажі, що утворюються у полум'ї. Запропоновано оригінальну методику для вимірювання масової швидкості горіння рідкого вуглеводневого пального. Проведено вимірювання температури фронту факела.