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ELECTRIC FIELD INTERACTION WITH HYDROCARBON FLAMES

The problem of electric-field-assisted combustion for low-melting point hydrocarbons (paraffin wax, n-alkanes) attracts the attention of scientists in relation to the development of paraffin-based propellants. Our study is aimed at the detailed investigation of the dc electric field interaction with the flame of octadecane droplet. We have studied the melting and combustion of alkane particles in the electric field ranging from 33 kV/m to 117 kV/m. It is found that the melting rate decreases distinctly starting with the electric field strength $E \sim 80$ kV/m. This effect is more pronounced at high gas temperatures ($Ste > 1$), when the melting time is about a few seconds. So, the melting process slows down in the dc electric field. At the same time, the burning rate constant rises by more than 10 percents. The obtained results can be used to develop efficient and clean technologies of fossil fuels combustion.

Keywords: combustion, flame, alkanes, electric field.

1. Introduction

In 2016, the oil's share of global energy consumption amounted to 32.9%. So, there is an urgent need to develop more efficient technologies of hydrocarbons combustion. Our research is focused on the use of a dc electric field to achieve the clean and efficient fuel combustion. It is known that any hydrocarbon flame contains charged species – ions, electrons, and soot particles. So, the flame can be treated as a low-temperature plasma. That is why an electric field influences the flame, including changing its shape, the sooting behavior, burning rate, and ignition limits [1]. The main way of ion formation in the hydrocarbon flame reaction zone is the radical reaction:

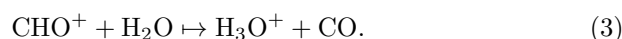


It is found that the formation enthalpy for a formil ion CHO^+ is rather low: $\Delta H_{\text{form}}(\text{CHO}^+) = 840 \pm \pm 20$ kJ/mole, so reaction (1) is practically insensitive to the temperature [2]. In addition to reaction (1), the collisions of vibrationally excited molecules CO_2 with

free electrons produce “hot” electrons in hydrocarbon flames:



The primary ions and electrons react with neutral particles producing a great number of secondary positive and negative ions. The end product of these reactions is oxonia ion H_3O^+ , which is observed in the burnt gas region:



It should be underlined that a great number of ion reactions occur in a flame. So, reactions (1)–(3) are the basic ones. The ion formation rate per C-atom consumed in hydrocarbon flames equals 0.25 coulomb/g-atom C. It is a practically constant value regardless the temperature and fuel structure [2]. Electrons and negative ions (C_2^- , C_2H^- , O^- , O_2^- , OH^-) are the negative charge carriers in the flame front. The soot particles are usually charged positively and bear one elementary charge. Thus, the external electric field acts on the listed charged particles, by producing the so-called ion wind. As a result, the size and shape of the flame front change resulting in the heat transfer enhancement. The promising applications of the

interaction on electric fields with flames were formulated by Lawton [1]: “direct” generation of electricity from rapidly glowing ionized flame gases; the control of some combustion processes by means of applied fields; modifying flame and carbon formation and deposition; the interaction of radio waves with rocket exhausts; the use of ionization probes in timing detonations and flame detection; controlling flames under zero gravity condition.

The application of electric fields is considered to be a highly promising approach to solve these problems. In addition to the above, a burning rate change under the action of an electric field is of particular interest and should be studied in detail. The analysis of research papers allows us to resume that the effect of an electric field on the combustion of gas mixtures has been studied extensively for a long time. The pronounced effect of an electric field on burning characteristics is confirmed by many experiments. To get an idea about the state of the art, one can read a comprehensive review by Tretyakov *et al.* [3].

The authors observed that, under the action of an electric field, the flammability limits of fuel-air mixtures expanded, the burning rate changed, and the flame stabilization shifted toward lean mixtures.

But a combustion behavior of solid and liquid fuels in an electric field is studied still insufficiently. In particular, the combustion of low melting point solid fuels (higher alkanes, paraffin wax) in an electric field is not studied yet. Last years, it becomes a very important issue due to the development of new paraffin-based propellants for hybrid motors. The use of the mechanisms developed for the combustion of gas mixtures does not explain the peculiarities of the condensed fuel burning in a dc electric field. The combustion behavior depends on the kinetics of phase transitions (melting and gasification) and the soot formation during the combustion.

Ilchenko and Shevchuk have studied the effect of a dc electric field on the combustion of liquid hydrocarbon fuels (methanol, hexane, benzene) by the stationary droplet method [4]. The electric field strength was varied from 0.5 to 2 kV/cm. It was found that the mass burning rate of benzene increased linearly with the field strength (the total gain reaches 15%), the burning rate of hexane increased slightly, and the burning rate of methanol was practically constant. Correspondingly, the droplet burning time reduced or did not change for methanol droplets. In

all cases, the flame was deflected toward the negatively charged plate of the capacitor. The deviation value increased with rising the electric field strength E and was more pronounced for luminous flames. The methanol flame was bent in the case of incomplete combustion (the appearance of a yellow glow). The authors considered the electric field influence on the burning processes and concluded that the ion wind through charged soot particles was dominant.

It should be mentioned some attempts to use a plasma for the fuel ignition and effective burning. V. Ya. Chernyak with co-workers investigated the possibility of using a non-equilibrium low-temperature plasma for the paraffin ignition and the combustion stabilization [5]. The plasma-assisted combustion of paraffin and stearin was studied experimentally by using a transverse and rotational gliding arc. The voltage-current characteristics of discharge were measured under the different operating conditions. The flame temperature profiles were calculated.

We can conclude that the results of previous studies are very promising regarding the electric-field control over the melting and combustion of alkanes.

2. Experiment and Discussion

Previously, the combustion of n-octadecane, n-docosane, and stearin droplets was studied experimentally, and the burning rate constants for different values of the initial droplet diameter were determined [6]. The experimental setup is improved to study the electric field effect on the droplet melting and burning. A flat capacitor consisting of two copper plates with dimensions 17×10 cm located vertically at a distance 6 cm is placed in the working space of the experimental setup. The plates are connected to a high-voltage source.

As the alkanes under consideration are solid at room temperature, a sample is to be melted at first in a water bath. Then a droplet is formed with a syringe needle and suspended on a tungsten filament loop ($d = 114 \mu\text{m}$). After the solidification, the droplet of a suspension is inserted in heated air, and the droplet heating and the burning history are recorded by a camera through a microscope objective ($\times 32$). During the droplet burning, its flame is recorded by another camera. The movies obtained are split into separate frames and processed by Image Processing Toolbox of MatLab. To determine the

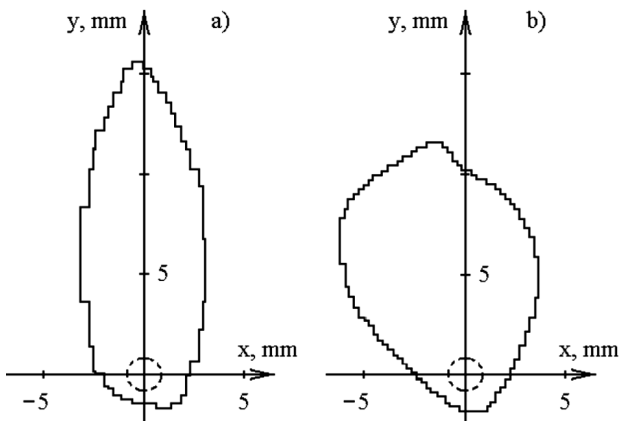


Fig. 1. Octadecane droplet burning: without electric field (a); in the electric field $E = 82 \text{ kV/m}$ (b)

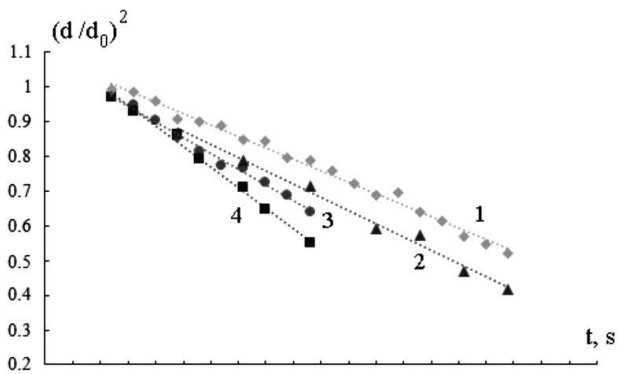


Fig. 2. Effect of a dc electric field on the burning rate of octadecane droplets: $d = 1.96 \text{ mm}$, $E = 0$ (1), $E = 82 \text{ kV/m}$ (2); $d = 1.64 \text{ mm}$, $E = 0$ (3), $E = 82 \text{ kV/m}$ (4)

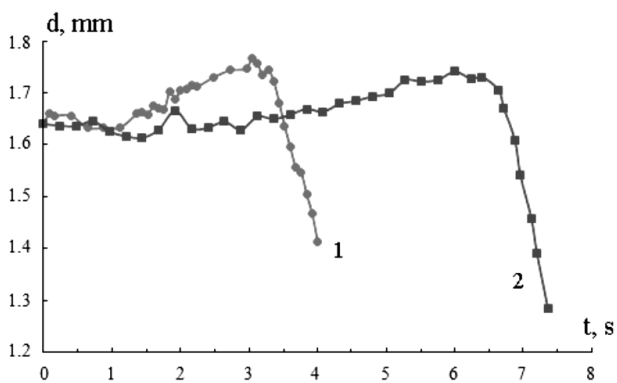


Fig. 3. Octadecane droplet size history: $d = 1.64 \text{ mm}$, $E = 0 \text{ kV/m}$ (1), $E = 82 \text{ kV/m}$, $T_g = 720 \text{ K}$ (2)

droplet equivalent diameter, an original method was developed. As the droplet shape is axisymmetric, we compute its surface area by the known formula for a surface of revolution and determine the corresponding value of the droplet equivalent diameter. Then we plot the graph of the droplet diameter squared versus the time $d_{\text{eq}}^2(t)$. A burning rate constant is defined as a slope of the linear part of the curve. The melting and combustion of alkane droplets (n-octadecane and n-docosane) are studied in a dc electric field in the interval from $33 \text{ kV/m} \div 117 \text{ kV/m}$. It is found that the melting rate decreases distinctly starting with the electric field strength $E \sim 80 \text{ kV/m}$. The effect of an electric field is more pronounced at high gas temperatures ($Ste > 1$), when the melting time is about a few seconds. Also the Quincke effect was observed, namely a solid residue rotation inside a melt in an electric field.

It is found that the burning rate constant significantly increases in a dc electric field. For octadecane, the droplet burning rate rises by $10 \div 20\%$ depending on the droplet initial diameter. It is observed that the flame deflects to the negatively charged plate, and its height diminishes. The intensification of the droplet combustion is explained by a significant increase of the radiation heat transfer from the luminous flame zone to the droplet surface due to a flame shape deformation. As a result, the evaporation process accelerates, and the burning rate increases as well. It should be noted that the electric field effect on the burning rate is noticeable starting with $E = 33 \text{ kV/m}$. To characterize the quantitatively flame shape, we use the aspect ratio factor, namely a ratio of a flame maximum extent to its maximum diameter in the perpendicular direction D : $AR = H/D$. We can see in Fig. 1 that the flame height and shape changed dramatically in a dc electric field: the flame height reduced by 40%, and the shape factor diminished approximately twofold from 2.7 to 1.3.

The radiation heat flux from the luminous region of a flame is proportional to the spatial angle $\Omega = \pi D^2/H^2$. So, it increases almost 4 times, and the radiation heat flux rises correspondingly. In Fig. 2, the square of the droplet diameter versus the time is presented. A significant rise of the burning rate constant in the electric field $E = 82 \text{ kV/m}$ is observed.

Thus, the promoting effect of a dc electric field on the alkanes burning is confirmed. The burning rate constants rise by about 15%, if the electric field

strength exceeds 80 kV/m, and the burning time of a droplet decreases correspondingly. But we should take into consideration that the droplet total combustion time equals a sum of ignition delay and burning time. In the case of low melting point alkane, the ignition delay comprises the pre-heating time and the particle melting duration. For this reason, we investigate the effect of a dc electric field on the alkane melting kinetics. To determine the melting rate and duration, we analyze the sequence of droplet images. It is found that the melting rate decreases distinctly starting with the electric field strength $E \sim 80$ kV/m.

The effect of an electric field is more pronounced at high gas temperatures ($Ste > 1$), when the melting time is about a few seconds. Moreover, the Quincke effect is observed, namely the solid residue rotation inside the melt in an electric field. The deceleration of the alkane melting in the electric field can be explained by the thermo-dielectric effect, namely the charge separation during the phase transition, which led to the appearance of a potential difference at the solid-liquid phase boundary ($0.3 \div 0.7$ V). As a result of the lack of mobile charges in the alkane volume, the phase boundary motion slows down.

There is an example of the droplet size history during the melting and burning in Fig. 3. It is well known that alkanes are characterized by a significant volume expansion during the melting. Hence, the droplet diameter increase is a good mark of the melting process. As soon as all substance is melted, the droplet ignites, its temperature rises abruptly, and the diameter decreases quickly. It is found that the melting time of octadecane droplets with an initial diameter of 1.64 mm equals 2 s without electric field. In an electric field, the melting time increases up to 4.5 s.

3. Conclusions

To summarize the data obtained on the combustion of low melting point alkanes in a dc electric field, we should underline that the effect of the electric field is ambiguous between an increase of the melting time

and a reduction of the burning time. This fact should be taken in consideration, when developing the systems for the electric-field-assisted combustion.

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ВЗАЄМОДІЯ ЕЛЕКТРИЧНОГО
ПОЛЯ З ВУГЛЕВОДНЕВИМ ФАКЕЛОМ

Резюме

Проблема спалювання в електричному полі легкоплавких вуглеводнів (н-алкани, парафін) привертає увагу дослідників у зв'язку з розробкою ракетного палива на основі парафіну. Мета даної роботи полягає у вивченні впливу постійного електричного поля на горіння октадекана. Для цього ми досліджували плавлення і горіння частинок алканів в діапазоні напруженості електричного поля від 33 кВ/м до 117 кВ/м. Встановлено, що швидкість плавлення помітно зменшується, починаючи з $E \sim 80$ кВ/м. Даний ефект більш виражений при високій температурі газу ($Ste > 1$), коли час плавлення становить декілька секунд. Таким чином, в електричному полі процес плавлення сповільнюється. У той самий час константа швидкості горіння зростає на 10% і більше. Отримані результати можуть бути використані для розвитку ефективних чистих технологій спалювання вихлопного палива.