

INFLUENCE OF THE ELECTRIC FIELD ON THE BURNING RATE OF ALKANES

S.G. Orlovskaya¹, F.F. Karimova¹, M.S. Shkoropado¹, V.Ya. Chernyak²

¹Odessa National I.I. Mechnikov's University, Odessa, Ukraine;

²Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

E-mail: svetor25@gmail.com

The effect of a homogeneous electric field on the burning of alkane particles in air is investigated. Stages of heat and mass exchange processes in the combustion process are determined. It is shown that the melting of a particle is the main constituent part of the induction period, the time during which the particle ignites. It is found that the melting rate is substantially reduced if the electric field strength exceeds a certain critical value. In our experimental conditions, it is about 60 kV/m. The effect of the electric field on melting is more pronounced at elevated temperatures and at high values of the Stefan number. The kinetics of the combustion of droplets of octadecane of various initial diameters was studied. It is proved that in a definite region of combustion the linear law of the square of the droplet diameter with time is fulfilled. The effect of an electric field on the burning rate of particles of different initial diameters is investigated. It is established that under the influence of the electric field, the burning rate of the droplets of alkanes increases. In particular, for droplets of octadecane, the burning rate in a constant electric field increases by 10...20 %, depending on the initial diameter of the drop. Constant burning droplets of octadecane are found. The effect of an electric field on the geometric dimensions of a flame is studied. It is established that under the influence of the field the flame becomes asymmetric and shifts towards the negatively charged plate. This reduces the height of the flame and increases its width. These phenomena are associated with the action of the "ion wind" in the flame and the transformation of the energy of the electric field into thermal energy, as a result of which the combustion front approaches the surface of the drop, increasing the rate of its evaporation. Calculations of the melting time of octadecane particles were carried out and a comparison was made with the data of experimental studies. The good agreement between experimental and calculated results is proved.

PACS: 536.46

INTRODUCTION

Straight-chain alkanes from hexadecane upwards form the important components of fuel oil and low-melting hybrid propellant. Also they are known as promising phase change material for latent heat storage. As far as the phase transitions solid-to-liquid play the special role in these applications so their melting characteristics are required. The data on melting kinetics are of particular interest in developing paraffin based fuel because just a melting duration determines in the main the ignition delay of paraffin particle. Multiple studies are aimed at enhancement of combustion efficiency and burning process stabilization. An application of electric field is considered to be a highly promising approach to solve these problems. It should be underlined that burning of gaseous fuels under electric field had been investigated for a long time. A 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. [1]. The authors resumed that under electric field the flammability limits of fuel-air mixtures expanded, the burning rate changed, flame stabilization shifted toward lean mixtures. Combustion of liquid fuels under an electric field is extensively studied last decade. It should be noted the investigation of Ilchenko and Shevchuk [2], which studied the characteristics of liquid hydrocarbon fuels combustion under dc electric field. They considered the mechanism of electric field influence on the burning processes and concluded that

the ion wind through charged soot particles was dominant. The temperatures in the flame front were measured.

In recent years an attention increased to the problem of combustion control in microgravity. So Ueda et al. [3] studied an influence of dc electric field on ethanol, n-octane and toluene droplets combustion. The observed increase in the burning rates of ethanol and n-octane was explained by convective enhancement through the electric wind. The convection velocity is estimated to be about 1...2 cm/s. During combustion a toluene droplet a streaming of a sooting flame was observed towards both electrodes. At the same time the effect of electric field on burning rate was more pronounced. The authors explained a significant increase of the toluene burning rate by radiation heat transfer to droplet surface due to flame deformation.

In so way, the ion wind is considered as dominant mechanism of electric field influence on burning rate. The combustion of non-sooting fuels accelerates mainly through convection. In case of sooting flames the main mechanism of combustion intensification is radiation heat flux from flame front to a droplet surface.

It should be noted that little information is available on burning of low-melting paraffin wax under electric field. But the results of previous studies are very promising regarding electric-field control of alkanes melting and combustion [4]. For that we studied melting and combustion of alkane droplets (n-Octadecane and n-Docosane) under different dc electric field ranging from 33 to 117 kV/m.

EXPERIMENT AND DISCUSSION

Detailed description of the experimental setup is presented in [4]. Since Octadecane and Docosane are solid at room temperature, a small amount of alkane is melted in water bath, and then a droplet is suspended on a thin filament (diameter 114 μm) from the tip of a syringe. After solidification the droplet is introduced into heated gas, and its evolution during melting, ignition and burning is recorded by two cameras: a flame is filmed by one camera and the droplet itself by another camera through microscope objective (x32). The movies obtained are split into separate frames and processed by using Image Processing Toolbox of MatLab. The evolution of droplet shape and size is analyzed to study kinetics of melting, evaporation and combustion. The method is developed to determine accurately the equivalent diameter of a droplet by computation its surface area [4].

A pendant drop has axisymmetric shape so we computed its surface area by well-known formula for surface of revolution, and then determined the droplet equivalent diameter as a diameter of a sphere having the same surface area [5]. In so way we calculated the values of droplet equivalent diameter for consecutive moments of time $d_{eq}(t)$. Then we plotted the graph of droplet diameter squared versus time $d_{eq}^2(t)$. So we substantially reduce the systematic error of evaporation and burning rate constants measurement. It was shown that the burning kinetics agreed with Sreznevsky formula (d^2 -law):

$$d_{eq}^2(t) - d_0^2 = K \cdot t.$$

Here d_0 – the initial diameter of a droplet, mm; K – a burning rate constant, mm^2/s .

A burning rate constant is defined as a slope of linear part of graph $d_{eq}^2(t)$. There are presented the frames of burning Octadecane droplet with initial diameter 1.96 mm in Fig. 1.

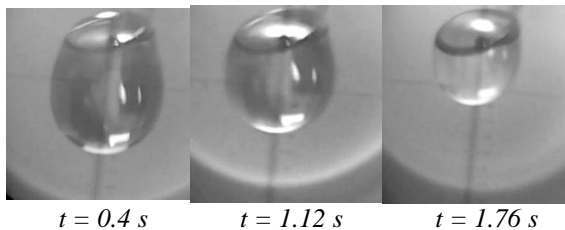


Fig. 1. Images of burning Octadecane droplet, $d_0 = 1.96 \text{ mm}$

In Fig. 2 the plots $d_{eq}^2(t)$ are presented for two Octadecane droplets ($d_0 = 1.64$ and $d_0 = 1.96$ mm), which were burnt without electric field (curves 1, 3) and under electric field (curves 2, 4). We can see that d^2 – law formula is applicable and the effect of electric field is distinctly expressed.

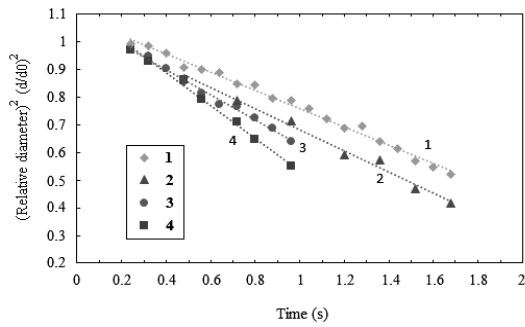


Fig. 2. The effect of electric field on burning rate of Octadecane droplet: $d_0 = 1.96 \text{ mm}$, $E = 0$ (1);

$E = 82 \text{ kV/m}$ (2); $d_0 = 1.64 \text{ mm}$, $E = 0$ (3);

$E = 82 \text{ kV/m}$ (4)

It should be noted that the electric field effect on burning rate is noticeable starting with $E = 3 \text{ kV/m}$. In order to explain this significant increase in burning rate we analyzed change of flame shape under electric field. It was found that the flame bended to the negative electrode, its height significantly diminished. The flame height histories during Octadecane droplet combustion are presented in Fig. 3.

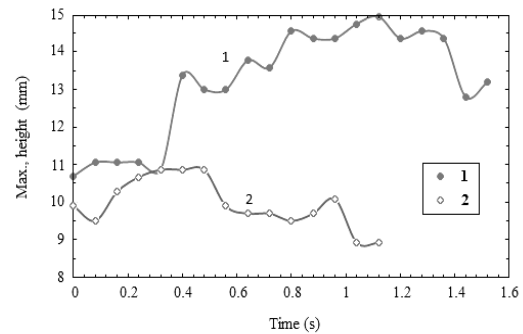


Fig. 3. Flame height histories of Octadecane droplet:

$d_0 = 1.64 \text{ mm}$, 1 – $E = 0$; 2 – $E = 82 \text{ kV/m}$

So the mean distance from flame front to the droplet surface diminishes significantly under dc electric field, and the radiation heat flux increases. As a result, fuel evaporation intensifies and mass burning rate rises too. It should be noted that this mechanism is applicable only in case of sooting flames. Ilchenko and Shevchuk [2] have shown that the drift of the soot particles is responsible for flame deformation and burning promotion. In case of non-sooting flame of methanol the effect of dc electric field is negligible. In fact it may be noticeable in microgravity conditions [3].

The most characteristic feature of higher alkanes combustion is the extended melting stage. Due to relatively high latent heat and low value of thermal conductivity its duration constitute an essential part of ignition delay. Therefore, we investigated a possibility to control a melting time of alkanes by dc electric field.

To determine a melting rate and duration we processed and analyzed the sequence of droplet images. It is found that melting rate decreases distinctly starting with electric field strength $E \sim 80 \text{ kV/m}$. The effect of 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 melt under electric field. The deceleration of alkane melting in the electric field can be explained by thermo-dielectric effect, namely charge separation during phase transition and arise of a potential difference solid-liquid phase boundary about 0.3...0.7 V. Due to the lack of mobile charges in alkane volume the phase boundary motion slows down.

There is an example of the droplet size history during melting and burning in Fig. 4. It is well-known that alkanes are characterized by significant volume expansion during melting, so a droplet diameter continuous 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 without electric field is 0.88 s, and under electric field the melting time increases up to 1.44 s.

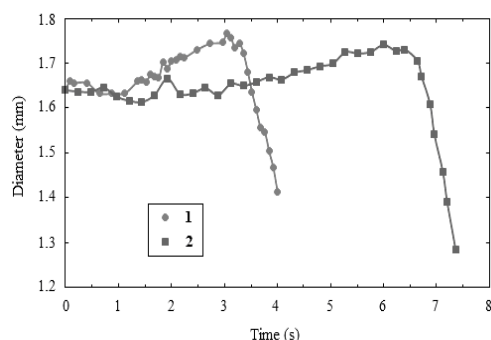


Fig. 4. Octadecane droplet size history: $d_0=1.64$ mm, 1 – $E=0$; 2 – $E=82$ kV/m, $T_g=720$ K

To estimate a melting stage duration we used the next formula [6]:

$$t_m = \frac{\Lambda \rho_l d}{6} \left(\frac{\lambda_g Nu}{d} (T_g - T_m) \right)^{-1}$$

Here Λ – a latent heat of melting; ρ_l – a specific density, g/cm³; d – a particle diameter, cm; T_m – a melting point of alkane, K.

The values of melting time (experiment and calculation) are presented for Octadecane droplet $d_0=1.64$ mm, $T_g=720$ K. There is a good agreement between experimental data and calculated values.

The melting times of Octadecane droplet

| d_0 , mm | t_m , s | |
|------------|-------------|------------|
| | calculation | experiment |
| 1.64 | 0.82 | 0.88 |
| 1.96 | 1.14 | 1.2 |

Thus the effect of dc electric field on higher alkanes combustion is rather ambiguous one: on the one hand the melting time increases, on the other hand the burning rate constant increases.

CONCLUSIONS

It is proved that when the droplets of alkanes are burning, the square of the droplet diameter decreases linearly with time. For drops of different diameters, the combustion rate constants, the shape and height of the flame in the combustion process are determined.

It is established that the electric field leads to an increase in the burning velocity of octadecane droplets and to the displacement of the flame in the direction of the field. In this case, the flame becomes asymmetric, its geometric dimensions are significantly changed: the height decreases and the width increases. These phenomena are associated with the action of the "ion wind" in the flame and the transformation of the energy of the electric field into thermal energy, as a result of which the combustion front approaches the surface of the drop, increasing the rate of its evaporation.

It is found that in a homogeneous stationary electric field the rate of melting of the octadecane particle decreases and, as a consequence, the melting time increases. It is proved that the melting of an octadecane particle in an electric field causes the unmelted solid phase to rotate in the melt, which is a manifestation of the Quincke effect.

The melting time of octadecane particles was estimated. It is obtained that the results of the calculation are in good agreement with the experimental data.

REFERENCES

1. P.K. Tretyakov, A.V. Tupikin, V.N. Zudov. Effect of laser radiation and electric field on combustion of hydrocarbon-air mixtures // *Combustion, Explosion, and Shock Waves*. 2009, v. 45, № 4, p. 413-420.
2. E.P. Ilchenko, V.G. Shevchuk. Role of charged soot grains in combustion of liquid hydrocarbon fuels in external electric field // *Ukrainian Journal of Physics*. 2005, v. 50, № 2, p. 144-150.
3. T. Ueda, O. Imamura, K. Okai, M. Tsue, M. Kono, J. Sato. Combustion Behavior of Single Droplets for Sooting and Non-sooting Fuels in Direct Current Electric Fields in Microgravity // *Proceedings of Combustion Institute*. 2002, v. 29, p. 2595.
4. S.G. Orlovskaya, V.V. Kalinchak, M.S. Shkoropado, F.F. Karimova. Investigation of the burning of paraffin droplets // *Ukrainian Journal of Physics*. 2014, v. 59, № 4, p. 396-400.
5. S.G. Orlovskaya, M.S. Shkoropado, F.F. Karimova, A.O. Odnostalko. Study of high-temperature heat and mass transfer and kinetics of phase transformations when combustion of higher alkanes in the air // *Physics and Chemistry of Solid State*. 2015, v. 16, № 2, p. 347-350.
6. S.G. Orlovskaya, F.F. Karimova, M.S. Shkoropado, A.A. Bondarenko. Investigation of the influence of the electric field on the melting of octadecane // *Physics and Chemistry of Solid State*. 2016, v. 17, № 2, p. 256-261.

Article received 16.09.2018

ВЛИЯНИЕ ЭЛЕКТРИЧЕСКОГО ПОЛЯ НА СКОРОСТЬ ГОРЕНИЯ АЛКАНОВ

С.Г. Орловская, Ф.Ф. Каримова, М.С. Шкоронадо, В.Я. Черняк

Проведено исследование влияния однородного электрического поля на горение частиц алканов в воздухе. Определена стадийность процессов тепломассообмена в процессе горения. Показано, что плавление частицы является основной составляющей частью периода индукции – времени, за которое частица воспламеняется. Обнаружено, что скорость плавления существенно уменьшается, если напряженность электрического поля превышает некоторое критическое значение. В наших экспериментальных условиях она составляет около 60 кВ/м. Влияние электрического поля на плавление более выражено при повышенных температурах и при высоких значениях числа Стефана. Изучена кинетика горения капель октадекана различных начальных диаметров. Доказано, что на определенном участке горения выполняется линейный закон изменения квадрата диаметра капли со временем. Проведено исследование влияния электрического поля на скорость горения частиц различного начального диаметра. Установлено, что под действием электрического поля происходит рост скорости горения капель алканов. В частности, для капель октадекана скорость горения в постоянном электрическом поле возрастает на 10...20 % в зависимости от первоначального диаметра капли. Найдены постоянные горения капель октадекана. Изучено влияние электрического поля на геометрические размеры пламени. Установлено, что под влиянием поля пламя становится асимметричным и смещается в сторону отрицательно заряженной пластины. При этом уменьшается высота пламени и увеличивается его ширина. Эти явления связаны с действием "ионного ветра" в пламени и превращением энергии электрического поля в тепловую, вследствие чего фронт горения приближается к поверхности капли, увеличивая скорость ее испарения. Проведены расчеты времени плавления частиц октадекана и выполнено сопоставление с данными экспериментальных исследований. Доказано хорошее согласие экспериментальных и расчетных результатов.

ВПЛИВ ЕЛЕКТРИЧНОГО ПОЛЯ НА ШВИДКІСТЬ ГОРІННЯ АЛКАНІВ

С.Г. Орловська, Ф.Ф. Карімова, М.С. Шкоронадо, В.Я. Черняк

Проведено дослідження впливу однорідного електричного поля на горіння частинок алканів у повітрі. Визначена стадійність процесів тепломасообміну в процесі горіння. Показано, що плавлення частинки є основною складовою частиною періоду індукції – часу, за який частинка спалахує. Виявлено, що швидкість плавлення суттєво зменшується, якщо напруженість електричного поля перевищує деяке критичне значення. У наших експериментальних умовах вона становить близько 60 кВ/м. Вплив електричного поля на плавлення більш виражено при підвищених температурах і при високих значеннях числа Стефана. Вивчена кінетика горіння крапель октадекану різних початкових діаметрів. Доведено, що на певній ділянці горіння виконується лінійний закон зміни квадрата діаметра краплі з часом. Проведено дослідження щодо впливу електричного поля на швидкість горіння частинок різного початкового діаметра. Встановлено, що під впливом електричного поля відбувається зростання швидкості горіння крапель алканів. Зокрема, для крапель октадекану швидкість горіння в постійному електричному полі зростає на 10...20 % в залежності від початкового діаметра краплі. Знайдено стала величина горіння крапель октадекану. Вивчено вплив електричного поля на геометричні розміри полум'я. Встановлено, що під впливом поля полум'я стає асиметричним та зміщується в бік негативно зарядженої пластини. При цьому зменшується висота полум'я і збільшується його ширина. Ці явища пов'язані з дією "іонного вітру" в полум'ї і перетворенням енергії електричного поля в теплову, внаслідок чого фронт горіння наближається до поверхні краплі, збільшуючи швидкість її випару. Проведено розрахунки часу плавлення частинок октадекану та зроблено співставлення з даними експериментальних досліджень. Доведено добру згоду експериментальних та розрахункових результатів.