Effect of electric field on alkane melting and burning

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Abstract. Melting and burning of suspended alkane droplets are studied experimentally under electric field. It is found that the melting rate substantially decreases if electric field strength exceeds some critical value. It is about 60 kV/m under our experimental conditions. Melting inhibition by electric field is more pronounced at elevated temperatures and high value of Stefan number. The rotation of solid core inside the melt is observed considered as manifestation of Quincke effect. The burning rate is found to increase significantly under dc electric field by 10÷20% depending on the droplet initial diameter. It was observed that the flame deflected to the negatively charged plate and its height diminished. The intensification of the droplet combustion is explained by significant increase of radiation heat flux from flame front to the droplet surface due to flame deformation. As a result the evaporation process accelerates, and the burning rate increases as well.

1. 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 kV/m to 117 kV/m.

2. 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):

\[
\frac{d_{eq}^2(t) - d_0^2}{K \cdot t}.
\]

Here \( d_0 \) – the initial diameter of a droplet, mm; \( K \) – a burning rate constant, mm²/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 Figure 1.

![Images of burning Octadecane droplet, \( d_0 =1.96 \) mm.](image-url)

Figure 1. Images of burning Octadecane droplet, \( d_0 =1.96 \) mm.
In Figure 2 the plots $d_q^2(t)$ are presented for two Octadecane droplets ($d_0=1.64$ mm 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.

![Figure 2](image)

**Figure 2.** The effect of dc electric field on burning rate of Octadecane droplet: 1-2. $d_0=1.96$ mm, $E=0$ (1), $E=82$ kV/m (2); 3-4. $d_0=1.64$ mm, $E=0$ (3), $E=82$ kV/m (4).

It should be noted that the electric field effect on burning rate is noticeable starting with $E = 33$ 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 Figure 3.

![Figure 3](image)

**Figure 3.** Flame height histories of Octadecane droplet: $d_0=1.64$ mm, 1) $E=0$ (3), 2) $E=82$ 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 ~ 80 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.

![Figure 4. Octadecane droplet size history: \( d_0 = 1.64 \text{ mm}, \ E = 82 \text{ kV/m}, \ T_g = 720 \text{ K} \)](image)

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

\[
t_m = \frac{A \rho_l d}{6} \left( \frac{\lambda_g \text{Nu}}{d} \left( T_g - T_m \right) \right)^{-1}
\]

Here: \( A \) – a latent heat of melting; \( \rho_l \) – 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 \( d_0 = 1.64 \text{ mm}, \ T_g = 720 \text{ K} \). There is a good agreement between experimental data and calculated values.
Table 1. The melting times of Octadecane droplet

| $d_0$, mm | $t_m$, s calculation | $t_m$, s 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.

References

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