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Original Article

A Study on Combustion Behavior of Ethanol Two Droplets in DC Electric Field under Microgravity

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Abstract

Combustion experiments of two droplets combustion were carried out in the DC electric field under microgravity. Two ethanol droplets are arrayed in the direction of electric field between two plate electrodes. As a result, flame deformations of anode-side flame and cathode-side flame are different from each other, but increases in burning rate constants are comparable level for two flames. This indicates different mechanism of effect of electric field for each flame. The convective effect is considered to be the main reason for cathode-side flame, on the other hand electron injection from the cathode-side flame is considered as the reason for anode-side flame. In order to discuss this phenomenon, droplets combustion in non-uniform electric field was also performed using a needle and a plate electrode, because electron emission will be expected when the needle electrode is negative. As a result, effects of electric field on flame deformations depend on polarity of electrode, however, effects on burning rate constant is comparable level in spite of polarity. From this experimental result, effect of electron injection is expected to appear as effect of local flow through negative ions. This effect of electron can be applied to anode-side flame in two droplets combustion and observed combustion behavior can be explained qualitatively.

1. Introduction

It is well known that flames contains many ions, electrons, and charged particles, (e.g. soot), and so external electric field affects flames through these ions[1]. Since droplets combustion is typical diffusion flame and it can be considered as a simple model of spray combustion, authors have been interested in the effect of electric field on the droplet combustion especially[2,3]. This kind of study is interesting scientifically because there is little study on the droplets combustion in electric field and, in addition, it can explore the possibility of combustion control using electric field. Authors studied mainly single droplets combustion in electric field up to now[2], however, not only single droplets but also droplets array combustion is important and interesting because an isolated single droplet does not exist in practical combustion chamber. From these backgrounds, authors studied *n*-octane two droplets combustion in DC electric field under microgravity, and showed that the effects of electric field depend on the distance between droplets and two individual flames can be affected by each other even when they have little interaction without electric field[3]. In addition, the effect of electric field on two droplet combustion is much larger than that of single droplets combustion. However, although *n*-octane flame forms suitable amount of soot to observe, soot itself has electric charges and this makes discussion complex. For example when soot particle in flame moves in the direction of electric field, movement velocity of soot is the sum of soot drift velocity, which is induced by soot's positive charge, and the neutral gas velocity (so-called ionic wind), which is induced by the fact that neutral gas is given momentum from ions driven by Coulomb force. In this case it is difficult to divide the effect through soot itself or through ions.

In this paper, ethanol is used as fuel because ethanol flame does not form soot at 1 bar and room temperature. Without soot, discussion becomes simple and effect of ions and electrons is revealed. In order to discuss the interaction effect between two separated flames in electric field, combustion experiments of two ethanol droplets in DC electric field were carried out with enough distance between them. All experiments are carried out under microgravity in order to eliminate natural convection. The interaction effects are discussed mainly from the behavior of flame shapes and droplet vaporization. In addition, in order to collect additional evidence, single droplet combustion in non-uniform DC electric field was also tested and effect of electron and negative ions is discussed.

2. Two Droplet Combustion in Electric Field

Figure 1 shows schematic of experimental apparatus for two droplet combustion. There are two parallel plate electrodes, which are wire nettings so as not to disturb the flow field around droplets. Each electrode is 60mm-square and distance between them is 50mm. The electric field between them is considered to be uniform without flame. As applied DC voltage between electrodes, V, are 0 to 6 kV in this study, equivalent electric fields are 0 to 120kV/m if they are uniform. Droplets, which are suspended by silica fiber 125 micro meters in diameter, are arrayed on the line jointing the center

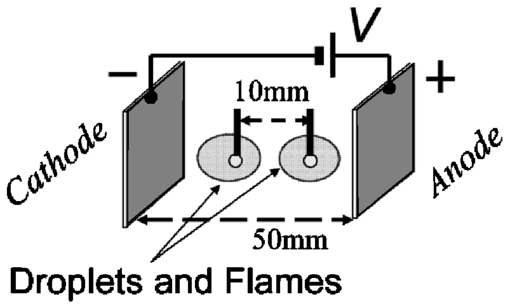

Fig. 1 Schematics of experimental apparatus (two droplets combustion)

of each electrode and the center point between droplets corresponds to the center point between the electrodes. Distance between droplets is 10mm for all conditions. For convenience, hereinafter the left flame, which is closer to the cathode, is called cathode-side flame, and the right flame is called anode-side flame.

There are a fuel supply system and a hot wire igniter beside the silica fibers, driven by a stepping motor and a rotary solenoid. They are not between electrodes during most of combustion time and disturbance on combustion from them is little. Combustion behavior is observed with two CCD cameras. One camera is to observe two flames and the other is to observe one droplet in closeup with backlit in order to obtain droplet's shrinking rate.

Figure 2 shows typical direct flame photographs of two droplets combustion in DC electric field. Direct photographs of single droplet combustion (using the same electrodes) are also shown for comparison. Anode is in the right side and cathode is in the left side of the flames for all photographs. As shown in this figure, all flames of two droplets combustion are individual during all combustion period and there seems to be no effect of two flame interactions without electric field. Figure 2 shows the cathode-side flame is deformed to cathode, which is similar to single droplet case, but on the other hand anode-side flame does not lean to one side, although it shrinks in comparison to flame without electric field. Since the degree of flame deformation of cathode-side flame is larger than that of single droplet case, it can be said that there is interaction effect between two flames specially for cathode-side flame.

In order to show the details of flame deformation, flame radii are defined as shown in **Fig. 3**. As shown in this figure, negative-side radius of flame towards cathode is defined as R_N for both anode-side and cathode-side flames. Positive-side radius towards anode and radius vertical to electric field are defined as R_P and R_V, respectively. **Figure 4** shows the flame radii of cathode-side flame divided by spontaneous droplet diameter as a function of time after ignition. This figure shows the flame radii divided by droplet diameter are roughly constant for all combustion

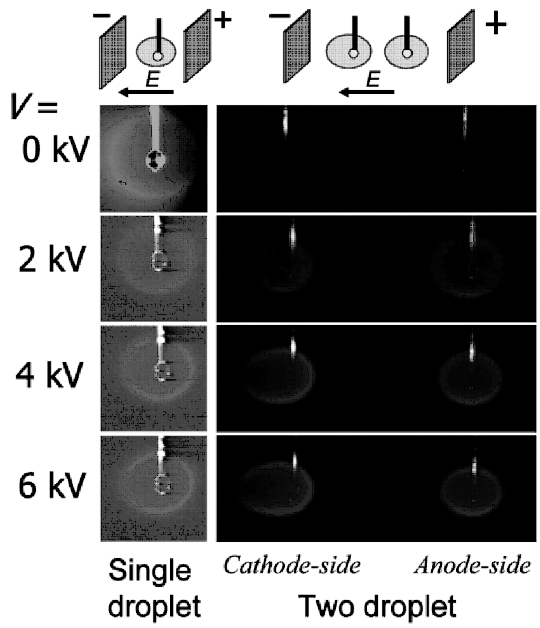

Fig. 2 Typical direct flame photographs (left: single droplets, right: two droplets)

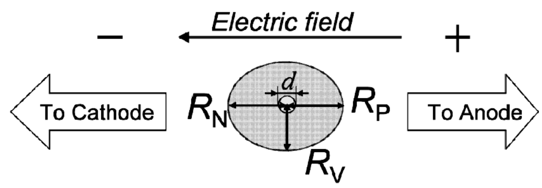

Fig. 3 Definition of flame radii

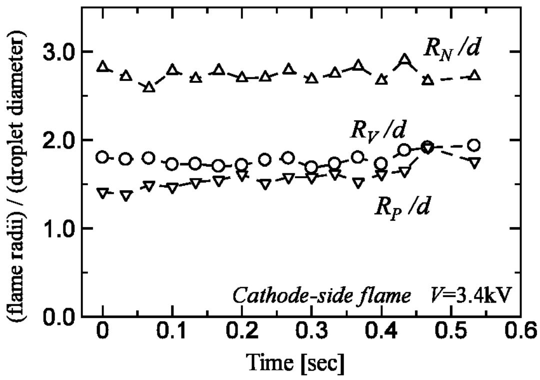

Fig. 4 Time histories of flame radii of cathode-side flame divided by spontaneous droplet diameter

period. Therefore the flame-droplet diameter ratios will be used for discussion of flame deformation with electric field.

Figures 5 and **6** show the relations between flame radii in two droplet combustion. Figure 5 shows the relations between positive-side and negative-side radii and Figure 6 shows the relations between positive-side and flame radii vertical to electric field. Judging from Fig. 2, the flame shapes of cathode-side flames seem to be similar to that under

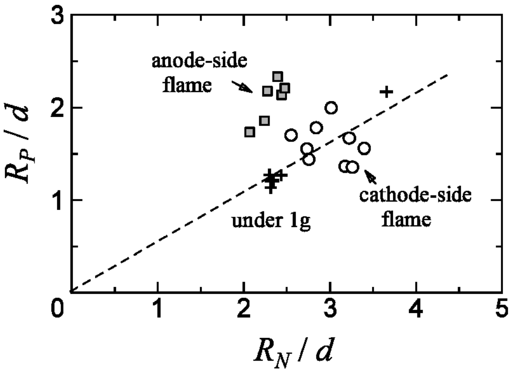

Fig. 5 Relations between positive-side flame radii and negative-side flame radii

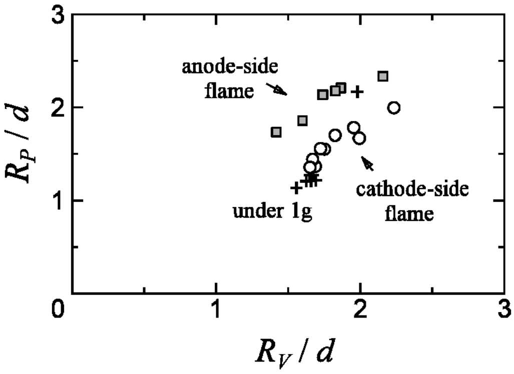

Fig. 6 Relations between positive-side flame radii and flame radii vertical to electric field

natural or forced convection. And so experiment results under natural convection (1g) are also shown in Figs. 5 and 6. Flame radii divided by droplet diameter in upstream side under natural convection, which are usually the bottom radii, are related to positive-side radii in two droplets combustion in electric field, and on the other hand flame radii in down steam are related to negative-side radii. Horizontal flame radii under natural convection are related to R_v in electric field. These figures show that flame shapes of cathode-side flame are quite similar to those under forced convection, but shapes of anode-side flame differ from those under natural convection. **Figure 7** shows the flame intensities on the line jointing the droplets. Abscissa axis show distance from each droplet center. This figure shows intensity distribution, which also shows the degree of flame deformation, is different between anode-side and cathode-side flames, as shown in Fig. 2. This figure also shows the intensities at the positive-side end of cathode-side flame are high. This indicates that chemical reaction is active at positive-side end of cathode-side flame. Consequently, effect of electric field on cathode-side flame can be explained by the convective effect induced by existence of anode-side flame. It is known that there are many ions and electrons in flame and most of negative career is electron at least in flame. Because of electric field, positive ions in

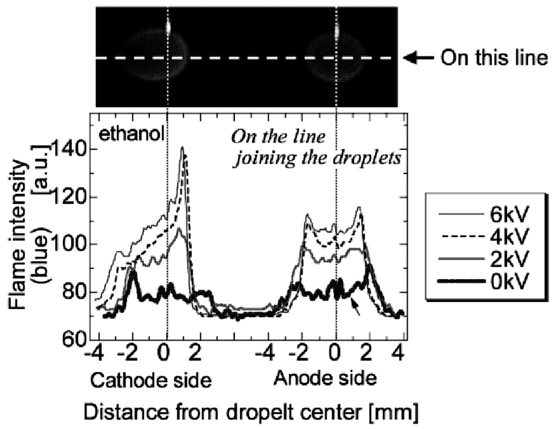

Fig. 7 flame intensities plotted as the function of displacement from droplet centers

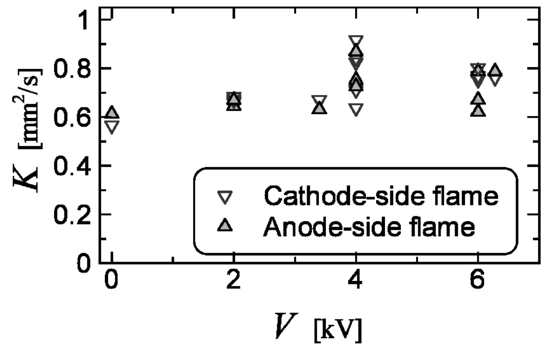

Fig. 8 Burning rate constants plotted as the function of applied voltages

anode-side flame move to cathode with colliding with neutral gas. Since the number density of neutral gas is much larger than that of ions, movement of neutral gas, which corresponds to convection from anode to cathode, becomes significant effect on combustion. This convection effect will be the reason for similarity of flame shapes between cathode-side flame and flames under natural convection. In addition, positive ions traveling from anode-side flame make the cathode-side flame charged positively and this is another reason for the flame deformation of cathode-side flame. However, because the convective effect from anode is strongly suggested from the flame intensity distribution shown in Fig. 7, the convective effect is dominant in comparison to effect of flame charge.

On the other hand, around anode-side flame not positive ions but electrons travel from cathode-side flame to anode. This point will be discussed in the next session.

Figure 8 shows the relationship between burning rate constants and the applied voltages. The burning rate constant, K, is determined from the slope of d^2 as the function of time until the other droplet burned out. Figure 8 shows the burning rate constants increase with the applied voltages and the differences cannot be found between anode-side

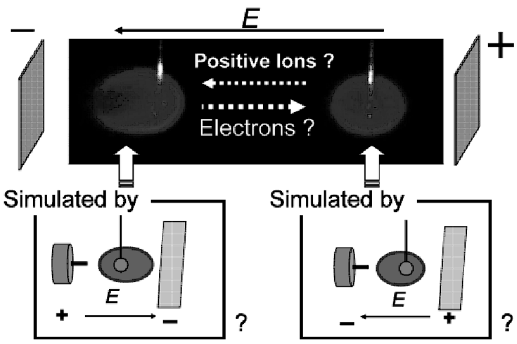

Fig.9 Concept of combustion experiments in non-uniform electric field

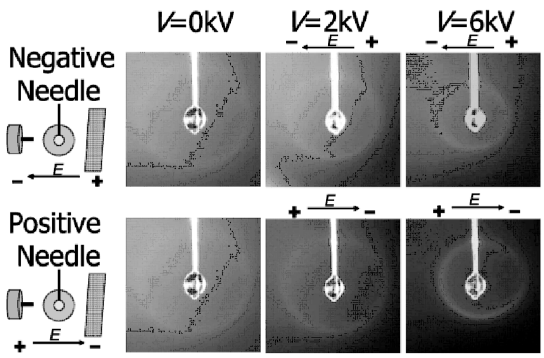

Fig.10 typical flame photographs in non-uniform electric field

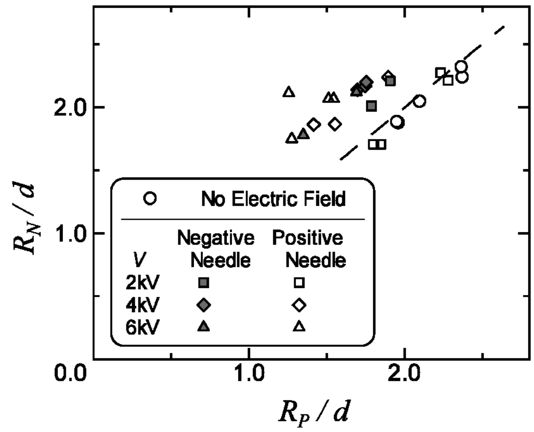

Fig. 11 Relations between anode-side flame radii and cathode-side flame radii in non-uniform electric field

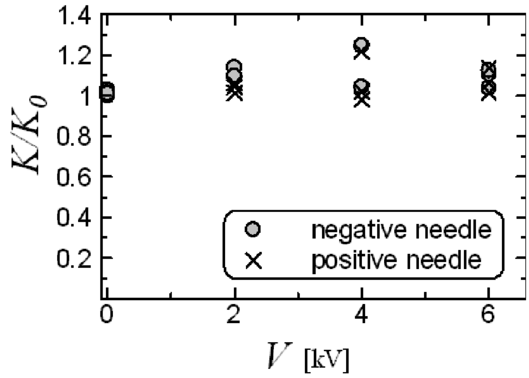

Fig. 12 Burning rate constants plotted as a function of applied voltages in non-uniform electric field

flame and cathode-side flame. Although differences can be seen in terms of flame shapes and intensities (Figs. 2 and 7), there is not so much differences between anode-side and cathode-side flames in terms of burning rate constants (Fig. 8). The increase of burning rate constants for cathode-side flame can be explained by convective effect that is mentioned above. However, it is hard to consider the same effect for anode-side flame because flame shapes are different from convective flame. It means the effects of electric field on combustion will be different between cathode-side and anode-side flames. In order to discuss this point, experiments in non-uniform electric field are tested.

3. Single Droplet Combustion in Non-Uniform Field

As mentioned above, the effect of electric field on combustion can be considered through positive ions because it is said that most of negative charge career in flame is electrons, which means negative charged careers give less momentum to the neutral gas due to its large electric mobility. This assumption is consistent with the experimental results of single droplets combustion in electric field[2]. For two droplets combustion in electric field, additional effect can be considered because positive ions and electrons travel from the other flames. The effect of traveling positive ions from anode-side flame to cathode-side flame is discussed in the previous session as the convective effect. In this session, effects of traveling electrons from cathode-side flame to anode-side flame is discussed. For anode-side flame, electrons are injected from the cathode-side flame.

In order to simulate the electrons traveling effects, experiments in non-uniform electric field are also carried out. The schematic of experimental apparatus and concept of this experiment are shown in **Fig. 9**. Electric field is formed by a needle electrode and a plate electrode. In this configuration, electric field is expected to be concentrated at the top of needle electrodes, and electron emission from the needle electrode is expected if needle electrode is negative. In this case, electrons will be injected to the flame and this is similar situation to anode-side flame in two droplet combustion. And so there can be some suggestion for anode-side flame in two droplet combustion. The distance between electrodes is 50mm and applied DC voltage between them is 0 to 6kV. Both electric polarities were tested, and hereinafter the case that needle electrode is cathode is called "negative needle". On the contrary case, that needle electrode is anode, is called "positive needle".

Figure 10 shows typical direct flame photographs of droplets combustion in non-uniform electric field.

This figure shows flame deforms to cathode in spite of polarity differences. This result indicates the flame deformation is principally explained by the effect through positive ions.

In order to illustrate the flame deformation, similar definition of flame radii is introduced as shown in Fig. 3. **Figure 11** shows the relations between R_P and R_N for flames of droplet combustion in non-uniform electric field. The dashed line shows R_P=R_N. This figure shows that the distribution of flame shapes of negative needle flame is smaller than that of positive needle flame. Except for 2kV, the distribution of negative needle flame is closer to that of flame without electric field and this means the flame deformation of negative needle flame is small in comparison to that of positive needle flame. **Figure 12** shows burning rate constants plotted as a function of applied voltages for single droplet combustion in non-uniform electric field. This figure shows the increase in burning rate constants is comparable level for negative and positive needle flame, although the flame deformation of positive needle flame is larger in Fig. 11.

For positive needle, the flame deformation can be explained through only positive ions effect. It is expected that, with increasing the electric field, wind induced by ions in flame becomes large and flame deformation becomes large. This convective effect is the reason for the increase in burning rate constant. For negative needle flame, although distribution of electric field is different, the tendency of flame shape with electric field should be similar and there is convection from anode to cathode if only positive ions effect is considered. However, flame deformation of negative needle flame is little in comparison to positive needle case above 4kV although the degree of increase in burning rate constant is not so much different. This will be caused by local flow effect from negative needle to positive plate. This arose from emitted electrons from needle electrode which will attached the neutral gas and make negative ions. If negative ions are formed, they cannot be ignored because they have small electric mobility and give enough momentum to neutral gas. This will make the local flow from cathode to anode between cathode (negative needle) and flame. These effects will appear as less flame deformation for negative needle case in Fig. 11. The effect will reduce the convection from anode to cathode and reduce the heat transfer to droplet, but because of opposite flow total heat and mass transfer to droplet will not change so much, which indicated Fig. 12. Another possibility can be also considered that the emitted electron from needle electrode makes the positive ions in flame decrease and consequently it reduces the wind from anode to cathode, but this mechanism explains only the flame deformation. And so the effect of local flow from cathode to anode seems to be dominant.

This effect of negative ions seems to be important for anode-side flame in two droplets combustion because electrons are traveling from the cathode-side flame to anode-side flame. It is possible that these electrons will make negative ions and induce the local flow from cathode to anode. Because of this local flow, the flame deformation of anode-side flame will be suppressed although the increase in burning rate constants is not so much different from cathode-side flame.

4. Summary

The combustion experiments of ethanol two droplets were carried out in the DC electric field under microgravity. Two ethanol droplets are arrayed in the direction of electric field between two plate electrodes. In addition, in order to discuss negative charged careers effect, single droplets combustion experiments in non-uniform electric field were carried out. Main conclusions of this study are as below:

1. Flame deformation and increase in burning rate constants are observed with electric field for any experimental condition in this study.
2. For cathode-side flame in two droplets combustion, the flame shape is quite similar to that under convection and the flame deformation and increase in burning rate constant will be caused by the convective effect induced by positive ions.
3. For anode-side flame in two droplet combustion, the flame deformation is smaller than cathode-side flame, although the increase in burning rate constant is not so much different. From the experimental results of droplets combustion in non-uniform electric field, the local flow effects induced by negative ions are suggested. Assuming this effect through negative ions, flame deformation and increase in the burning rate constants can be explained qualitatively.

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References

1) Bradley, D., "The Effects of Electric Fields on Combustion Process" *in* Advanced Combustion Methods", Academic Press Inc., 1986, pp.331-394
2) Ueda, T., Imamura, O., Okai, K., Tsue, M., Kono, M., and Sato,J., *Proc. Combust. Inst.* **29**, 2595, 2002.
3) Okai, K., Ueda, T., Imamura, O., Tsue, M., Kono, M., Sato, J., Dietrich, D.L., and Williams, F.A., *Combust. Flame,* **136,** 390, 2004.

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