論 文 の 内 容 の 要 旨

論文題目　　A Study of Droplet Combustion Behavior in Electric Fields
（電界中における液滴燃焼挙動に関する研究）

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1. Introduction

Hydrocarbon droplet fuel combustion is related to spray combustion technology with hydrocarbon fuel because it is possible to consider spray combustion as the integration of droplet combustion. Spray combustion can be seen in many fields of engineering like mechanical, heavy industry, chemical plant and aerospace. Although the cases where single droplet combustion is applied are never seen, research on droplet combustion phenomena leads to the understanding of complex spray combustion engineering. And now, the gravity environmental of this research, microgravity environmental, is lead to the development of combustion utilization and fire safe technology in the space ship. In the future, the opportunity using the combustion in space will increase as development of space. It would be necessary to utilize the combustion techniques safely in the future.

Furthermore, the application is in the global environmental saving field. The deformation of a flame caused using an electric field makes it possible to control heating. The enhancement of heat transfer caused using an electric field also lead to efficiency heating. Heating efficiency is important because of the global issue of warming. Actually, use of combustion techniques plays a major role of this issue. Additionally, the suppression of pollution like soot or NO_x is important from the view point of global environmental saving. It would be clearly that this research has importance and relevance worth from both the engineering and environmental field.

The phenomenon of combustion under electric fields has been revealed quantity in past studies. On the other hand the numerical simulation has been not much done because of the calculation load and complexity. It is, however, needed that this combustion phenomenon under electric fields is researched numerically because the experimental measurement is restricted for the high voltage and microgravity conditions. For these backgrounds the analysis of droplet combustion under electric fields for the cases with and without soot particles production is carried out experimentally and numerically.

2. Experimental and Numerical method

All experiments are carried out under microgravity environment to remove the natural convection effect. The time history of fuel droplet diameter is measured by image analysis from direct photographs of flame and droplet fuel in order to obtain the burning rate constant.

Numerical simulation is carried out calculating the conservation of mass, momentum, energy, species and charge equations. Additionally the electric equations, evaporation equations considering the interaction between combustion gas and liquid fuel droplet, particle tracking equations considering the interaction between combustion gas and soot particle are calculated. The numerical simulation model is examined and found to be qualitatively reliable. In the simulation of porous burner diffusion flame and spherical electric field, the effect of ionic wind under electric field is predicted and compared with the experimental results. Although there is some discrepancy with experimental results with maximum temperature and OH radical, the movement of flame is occurred and the numerical model is adopted the basic model of ethanol and n-octane droplet combustion simulation.

3. No sooting flame behavior

Droplet combustion without the soot particle generation is researched using the ethanol fuel experimentally and numerically. Fig. 1 shows the calculation field to simulate the droplet combustion behavior under electric fields. The gas phase (Combustion gas) is calculated in 2-Dimensional body fitted coordinates and 40 hoop grids, 40 radial grids, total of 1600 grids. Meanwhile the liquid phase (Droplet fuel) is calculated at the center of calculation field. Both ethanol and octane fuel combustion are predicted at this field. On the ethanol case, electric fields strength condition is considered at two cases which include it is independent and dependent with electric potential profile.

In the experimental results, the normalized burning rate constant is increasing with the applied voltages in a monotone as Fig. 2. Also the rate of flame deformation is increasing with the applied voltages, it is thought that there is local strong flow as Fig. 3. The numerical results are compared with the experimental results with several applied voltage cases as Fig. 2. Closer prediction with experimental results is obtained with variable case as Fig. 3 and it is suggested that effects of charge density on the electric fields strength is important.

The mechanism of combustion enhancement by deforming flame with uniform electric fields is investigated. Increases in heat transfer from flame gas to fuel droplet surface resulting from change of relative distance between flame and droplet surface is shown. Furthermore the deformation mechanisms of flame considering the local induced flow, changing of electric potential and field, charge density profile is also investigated. The OH radical and velocity vector profile with and without electric fields is shown in Fig. 4. Namely, the electric potential is profiled constantly just after ignition of droplet because of the initial applied uniform electric fields. However, the ionization reaction proceeds at the high temperature zone of flame and then many positive and negative ions are generated. For these generated charge, the concavity and convexity are occurred in the electric potential profile. Furthermore the ion and electron are driven by the electric fields which depend on the changing electric potential. At that time it is considered that these charged species collide with the neutral air molecule. As a result the exchanges of momentum between charged species and air molecule are occurred and it causes the local flow. For this induced flow, the flame is deformed and the distance from anode side flame and droplet surface become shorter and from cathode side flame and droplet surface become longer. Additionally the amount of heat inlet from flame to the droplet surface become larger, then the droplet temperature is increasing rapidly and evaporation is enhanced. Consequently the burning rate constant is increased. The underestimation of flame deformation in calculation results is explained by considering of insufficient ion reaction mechanisms and assumption of fixed droplet surface position.

4. Sooting flame behavior

Droplet combustion with the soot particle generation is researched using the n-octane fuel experimentally and numerically. Although the calculation coordinate is same as the ethanol case, 40 hoop grids, 50 radial grids, total of 2000 grids are adopted. The calculation of solid phase (soot particle) is added and then the jointed analysis of the multiphase flow which includes the gas phase, liquid phase and solid phase with the electric fluid which includes the electric fields, potential and charge is carried out. Fig. 5 shows the comparing of flame photograph with ethanol and n-octane fuel under two electric fields conditions. Obvious difference of deformation rate between ethanol blue flame and n-octane luminous flame is shown. Noticeable difference between these fuels is to produce the soot particle inside the flame. Additionally the blue flame can be seen all around the droplet fuel even if the electric fields is applied with ethanol droplet combustion. However the luminous flame can not be seen all around the droplet fuel when high voltage is applied with n-octane droplet combustion. The strong luminous flame is seen in the cathode side and wake emission is seen in the anode side. This result shows that the soot particles which have the self luminous character are moved to the cathode side and gathered closely. Therefore the effect of soot particle on the induced flow under electric fields is focused. The simplified model of soot production is adopted and the flame deformation under uniform electric fields is predicted. Fig. 6 shows the temperature and velocity profiles obtained in the numerical simulation. In the 4kV voltage applied case, the remarkable deformation of flame and induced flow from anode to cathode side are shown. Additionally the time historical soot particle profile at representative time is shown in Fig. 7. From this results, it is thought that the charged soot particles is moved along with the stream line and give the flow field local increasing of momentum. Namely the soot particles under electric fields are mainly charged to the positively. Due to this, the soot particle in the n-octane case behaves like positive ion species in the ethanol case. Additionally due to its volume fraction, much exchange of momentum between soot particle and ambient gas is occurred than that of ion species case. As a result the strong flow is caused locally. To investigate this ascendant of soot particle to ion species, the no soot particle n-octane flame is simulated virtually and then the importance of soot effect on the flame deformation is denoted. The relation between burning rate constant and applied voltages is investigated. The results are shown in Fig. 8. In this figure, time history of droplet diameter with experimental and numerical analysis. The increase of burning rate constant in the numerical simulation is few than that of experimental results. It is described that this discrepancy between numerical and experimental results are depend on the prediction of soot production, the imprecise flame which is caused by the reduced chemical reaction model, the disregard of radiation effect from soot particle and the rough grid settings.

5. Conclusion

In this report, the droplet combustion behavior under uniform electric fields with and without soot particles is researched. Several conclusions obtained in this research are following;

- In the case where the electric fields strength is varied with the local charge density, the numerical prediction of flame deformation becomes closer to the experimental results than that of constant electric field strength case.
- Increases of inlet heat amount to the droplet surface are shown when high voltage is applied between plate electrodes.

- The deformation of flame and changes of flow field are predicted. Those occurring mechanisms are explained considering the given Coulomb force which depends on the electric fields strength and charge density.
- The underestimation of flame deformation with ethanol droplet flame is explained that because the adopted ion reaction mechanism is imprecise, the induced flow is weak to change the flame shape.
- The overestimation of burning rate constant with ethanol droplet combustion is explained that the fixed droplet surface position cause the underestimation of distance between flame and droplet surface. Furthermore the ignoring of radiation heat loss cause the overestimation of high temperature flame, then the droplet is vaporized excessively.
- The simplified soot generation model is adopted for predicting the n-octane droplet flame under uniform electric fields. Obvious deformation and induced flow is shown in the numerical results.
- Soot particle movement along with the stream line is shown and the interaction between charged soot particle and ambient combustion gas is considered.
- The importance of soot particle effect on the n-octane droplet flame is explained with the virtual no sooting n-octane droplet combustion simulation.
- The underestimation of burning rate constant with n-octane droplet flame is explained that the assumption of reduced chemical reaction mechanism cause the imprecise flame structure.
- Although it is not complete numerical model because of many assumptions, the experimental and numerical analysis of droplet combustion behavior under electric fields which have not been done in past is carried out and adequate result is obtained partially.