Numerical Study on Flame Propagation Mode of Linear Fuel Droplet Array System

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1. Introduction

There are many studies on the combustion process of single-fuel droplet or multiple-droplet systems, such as a droplet array and matrix. Those studies are expected to lead to improved understanding of spray combustion through the clarification of composed droplet combustion characteristics.

The objectives of the current research are clarification of the flame propagation mechanism of a fuel droplet array using a microgravity environment as a highly useful tool, and establishment of a reasonable model for improved understanding of more complex spray combustion mechanisms. The present study describes unsteady flame propagation mechanisms in a linear fuel droplet array. This study includes numerical analysis that revealed a detailed flame propagation process, and a microgravity experiment utilizing advanced experimental techniques. First, through the theoretical considerations, we have classified characteristic modes of flame propagation of a fuel droplet array, and, a combustion mode map was constructed. This mode map predicts the mode that should be expected at given environmental and geometrical conditions of a droplet array, where non-dimensional ambient temperature and droplet spacing are characteristic parameters. Next are an overview of numerical simulations and microgravity experiments, and a comparison of their results.

2. Theoretical Prediction: Flame Propagation Modes of Linear Fuel Droplet Array

With detailed theoretical analysis, Umemura [1] revealed and classified five types of flame propagation modes of a linear liquid fuel droplet array in an atmospheric environment. Figure1 indicates that the appearances of combustion modes depend on two non-dimensionalized characteristic parameters. One is the non-dimensional ambient gas temperature *RT/L* (*R*: ambient gas constant, *T*: Ambient gas temperature, *L*: Liquid fuel latent heat); the other is the non-dimensionalized inter-droplet distance *S/d* (*S*: inter-droplet distance, *d*: droplet diameter). The five flame propagating modes classified are briefly explained as follows:

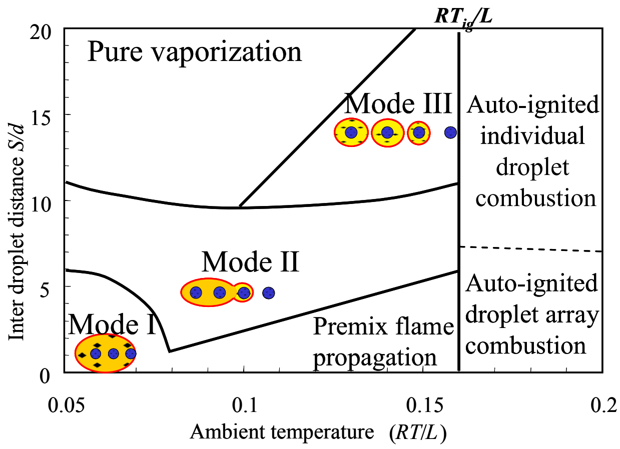


Fig. 1 Theoretical flame propagation mode map

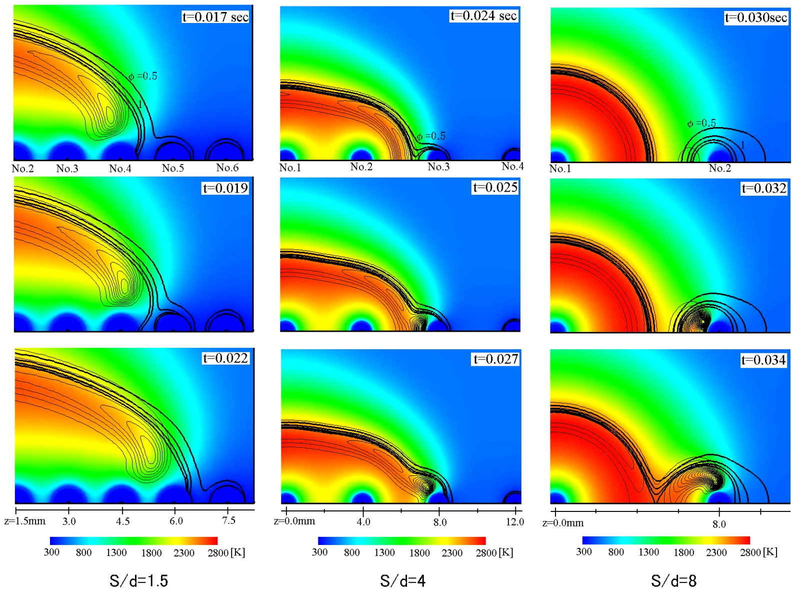
With a high ambient temperature, which is sufficient for self-ignition of droplets, the droplets are automatically ignited, burn, and form independent diffusive flames around themselves or a group combustion flame (**Auto-ignited combustion mode**). With a low ambient temperature and large inter-droplet distance, the forced-ignited droplet flame cannot propagate along a droplet array, so the non-burning droplets simply evaporate (**Pure vaporization mode**).

Between two parameters, three modes (I, II, and III) of flame propagation are expected. In **Mode I**, unburned droplets are enclosed by a rapid propagating diffusive flame, and then this activates its vaporization. The activation of vaporization becomes the driving force of consequent spreading of the flame. Along a droplet array, this sequence is repeated and the droplets enter group-combustion mode. If the ambient temperature is high enough to form a united combustible premixed vapor layer around the array, the flame propagates in this layer. In **Mode II**, the propagating flame activates vaporization of unburned droplets and ignites the premixed vapor around the droplets. Then, ignited droplets immediately form a diffusive flame and enter group combustion. In **Mode III**, the same sequence as in mode II would occur until ignition, but the difference is that the ignited droplets form diffusive flames independently, and never enter group combustion.

Over the two-parameter plane (*S/d* - *RT/L*), the flame propagation mode map is constructed with the five modes mentioned. An important point to mention is that the mode map can be applicable to any kind of less-volatile liquid hydrocarbon fuel. Regarding this mode map as a guide to subsequent numerical simulations and microgravity experiments, this flame propagation phenomenon was investigated and the the mode map was cross-examined.

3. Numerical Simulation of the Flame Propagation Process of a Droplet Array

In the numerical analysis, the mass, momentum, energy, and five chemical species (n-Decane, O_2, H_2O, CO_2, N_2) mass concentration conservation equation system was numerically solved. n-Decane served as a less-volatile liquid fuel in order to compare the results with microgravity experiment data.



(a) (b) (c)

Fig.2 Numerical results of flame propagation (d = 1mm, T = 573K, Thick line: contours of equivalence ratio, thin line: contours of reaction rate)

An example of calculated results is shown in Fig.2. The n-Decane droplet array is placed along the centerline of axisymmetric coordinates in stagnant air. The bottom line of the analytical domain corresponds to the center axis of a droplet array. The left-side droplet is forced-ignited by addition of an artificial heat source. The flame propagates from left to right. The combustion process was supposed to be axisymmetric, and a one-step reaction mechanism was employed (for details, see Ref. [2]).

Figure 2 (a) indicates that the flame front travels straight along the short-spacing droplet array through the premixed gas layer. The temperature between droplets is remains low due to the strong cooling effect of vaporization. Figure 2 (b) indicates that the propagating flame front ignites the combustible gas layer formed around an unburned droplet. In addition, the process of development of a premixed flame around ignited droplets is well understood. In Fig.2(c), the premixed flammable gas layer around an unburned droplet ignites before the droplet is reached by flame front.

These results readily ascertained the characteristic modes of flame propagation predicted by theoretical consideration. Via this numerical analysis, flame propagation mechanism based can be explained from a microscopic viewpoint.

In addition to numerical analysis, we have started the drop-shaft experiments utilizing the facility of the Microgravity Laboratory of Japan (MGLAB), where a good microgravity environment, at a 10^{-5}g level for 4.5sec duration, is available for users.

Figure3 is the typical direct image of each flame propagating modes (I to III) obtained by a Sony DV camera. In the figure, the environment temperature is set to 300K. The experiment temporal images correspond to each mode, establish the qualitative correctness of theoretical prediction, and display good agreement with numerical results. Figure4 show temporal color contour images of [OH] radical emission in flame propagation mode III (time interval: 2ms). In the figure, the left-side burned droplet ignites the premixed vapor layer around the right-side unburned droplet. The premixed flame appears to propagate around the droplet with a triple-flame structure.

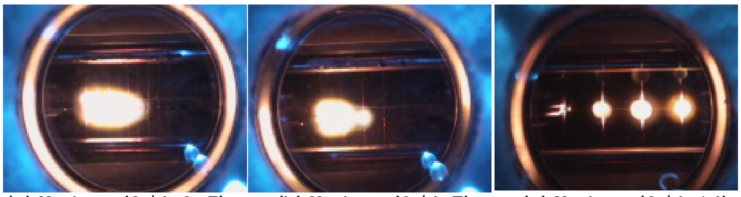

(a) Mode I (S/d=3.5) (b) Mode II (S/d=7) (c) Mode III (S/d=14)

Fig.3 Flame propagation images in microgravity experiments

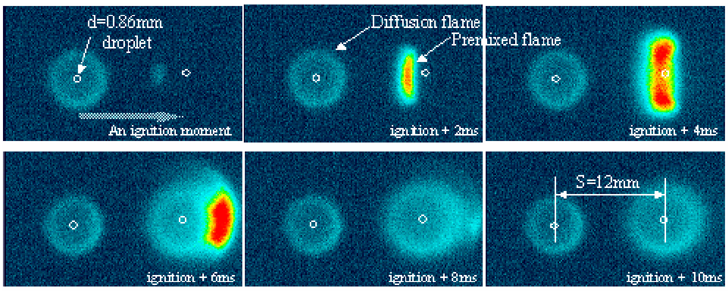


Fig.4 Flame propagation process of Mode III by [OH] radical imaging

4. Summary

With theoretical prediction, the unsteady flame propagation process (transition to Q-S Combustion state) of a linear droplet array was investigated using a numerical method. The results display good agreement with theoretical study and are verified by microgravity experimental data. In further analysis and comparison with experiment data, details about flame propagation mechanisms and combustion characteristics of a droplet array will be clarified.

References

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