Numerical Study on Flame Spread of a Linear Fuel Droplet Array in Fuel Vapor-Air Mixture

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1 Introduction

Flame spread of a linear fuel droplet array has been investigated by many researchers [1-4]. It is expected that such investigations provide fundamental knowledge for better understanding of flame propagation mechanism of fuel spray, since flame spread of a linear fuel droplet array would be the simplest configuration to study flame spread mechanism among fuel droplets.

Kikuchi et al. have also studied flame spread mechanism of a linear n-decane droplet array by numerical simulations as well as microgravity experiments [5,6], in cooperation with experimental study by Mikami et al.[4]. In our past research, fundamental flame spread mechanism of a linear fuel droplet array, such as effects of droplet interval S and ambient temperature T on flame spread phenomena, was investigated for the droplet array without pre-vaporization [5] and with pre-vaporization [6]. Experimental results with pre-vaporization showed occurrence of characteristic shape on OH radical emission at spreading flame front as well as increase of flame spread rate V_f with increase in degree of pre-vaporization. Also, numerical results indicated the experimentally observed characteristic shape on OH radical emission to be triple flame structure.

In the previous study with pre-vaporization of the droplets [6], gas layer of fuel vapor-air mixture was assumed to be formed around the droplets with fuel concentration gradient. Considering real spray combustion, however, fuel vapor-air mixture would exist as the ambience, in addition to the gas layer with fuel concentration gradient in the vicinity of the droplets. Therefore, effects of fuel vapor-air mixture on flame spread of a linear n-decane droplet array are numerically investigated in this study. Also, comparison of the numerical results with related experimental results in microgravity by Suganuma et al. [7] will be shown.

2 Numerical method and results

In this study, similar numerical method as our past study [5] was employed. Figure 1 shows calculation domain and boundary conditions. The domain is based on axisymmetric, two-dimensional cylindrical coordinate, since flame spread phenomena in microgravity are supposed. Open boundary conditions are applied for outer boundaries. Gas flow velocity, temperature, and mass fraction of chemical species at outer boundaries are extrapolated from inner domain in accordance with the constant pressure (P = 0.1 MPa) at the boundaries. Also, zero gradients of physical variables are considered along the axisymmetric center line (r = 0). A droplet at the left edge of the array is ignited by a heat source. Fluid flow, temperature, and mass fraction of chemical species

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are calculated with time. One step overall reaction was employed in this study. N-decane, O_2, N_2, CO_2, and H_2O were considered as chemical species. In the previous study [5], there was no fuel vapor-air mixture in the ambience as the initial conditions. Therefore, equivalence ratio of the ambient gas ϕ_g was 0 as initial conditions for all cases. In the present study, on the other hand, calculations with various ϕ_g were conducted in different *S* to study the effects of ϕ_g on flame spread behaviours of the droplet array. As for ambient temperature *T*, it was decided depending on the intended ϕ_g, following the relation on saturated vapor concentration at *T*.

Examples of numerical results with S = 2 mm are shown in Fig.2 (a) and (b), for ϕ_g = 0 and 0.7, respectively. Temperature distribution, contours of reaction rate and equivalence ratio are indicated by gray scale, gray lines and white lines, respectively. In Fig.2 (a), front of the diffusion flame, surrounding multiple droplets, advances forward by development of the diffusion flame. In Fig.2 (b), on the other hand, premixed flame propagates in the fuel vapor-air mixture at first, since ϕ_g is larger than the lean flammable limit of n-decane and air mixture (roughly ϕ_g = 0.5). After propagation of the premixed flame, a diffusion flame is formed around the droplet array. So, it was numerically demonstrated that flame spread behavior of the droplet array is affected by existence of fuel vapor-air mixture as the ambience. Also, similar numerical results with S = 12 mm are shown in Fig.3 (a) and (b), for ϕ_g = 0 and 0.7, respectively. In Fig.3 (a), flammable gas layer around unburned droplet ignites by heat from burning droplets. In this case, flame spreads in a stepping-stone manner. In Fig.3 (b), on the other hand, propagating premixed flame ignites unburned droplets to form a diffusion flame around the droplet. From these results, it was indicated that flame spread or propagation mechanism is significantly affected by the value of ϕ_g.

In addition, flame spread rate V_f normalized by d_0, as a function of ϕ_g for numerical simulations and results of microgravity experiments by Suganuma et al. [7], is shown in Fig.4. V_f increased with increase in ϕ_g both for numerical and experimental results, although V_f of numerical simulations is larger than that of the experimental results. Also, differences in numerically obtained V_f for different *S* decrease with increase in ϕ_g. This is because propagation speed of premixed flame dominates V_f when ϕ_g is within flammable range.

3 Summary

Effects of fuel vapor-air mixture on flame spread of a linear n-decane droplet array are numerically investigated. It was indicated that flame spread behaviors and flame spread rate V_f are significantly affected by the value of ϕ_g, equivalence ratio of fuel vapor-air mixture as the ambience. For detail clarification of the phenomena, further investigations, such as detail comparison of the numerical results with the related experimental results or additional numerical analysis, are ongoing. The latest result will be shown in the presentation.

Acknowledgements

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References

[1] Brzustowski, T. A., Sobiesiak, A. and Wojcicki, S. (1981). *Proc. Combust. Inst.* 18, pp 265-273

[2] Okajima, S., Kimoto, T., Abe, K. and Yamaguchi, S. (1981). *Trans. Jpn. Soc. Mech. Eng. (in Japanese)*, B47(422), pp 2058-2065

[3] Kobayashi, H., Park, J., Iwahashi, T. and Niioka, T. (2002). *Proc. Combust. Inst.* 29, pp 2603-2610

[4] Mikami, M., Oyagi, H., Kojima, N., Kikuchi, M., Wakashima, Y. and Yoda, S. (2005). *Combust. Flame*, Vol.141, pp 241-252

[5] Kikuchi, M., Wakashima, Y., Yoda, S. and Mikami, M. (2005). *Proc. Combust. Inst.* 30, pp 2001-2009

[6] Kikuchi, M., Sugano, N., Yoda, S. and Mikami, M. (2007). *Proc. 6th Asia-Pacific Conference on Combustion*, pp 639-642

[7] Suganuma, Y., Nomura, H., Ujiie, Y., Kikuchi, M., Yoda, S., and Mikami, M. *J. JSME Trans. B (in Japanese)*, submitted

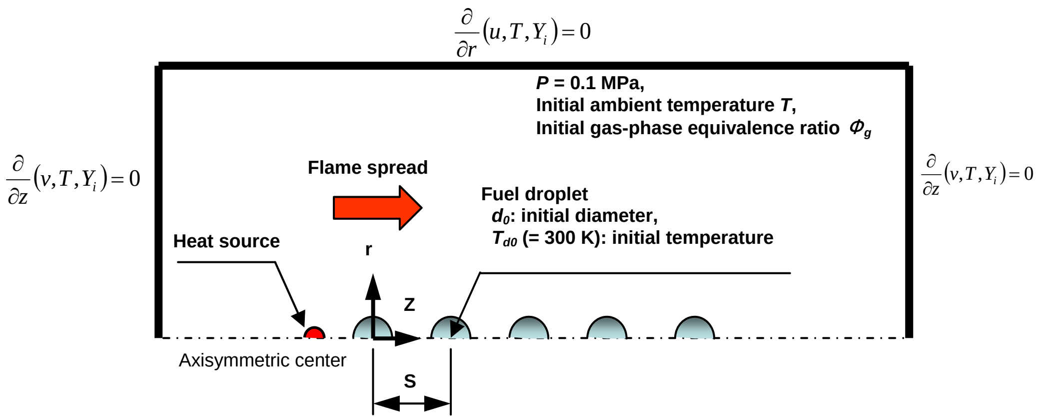
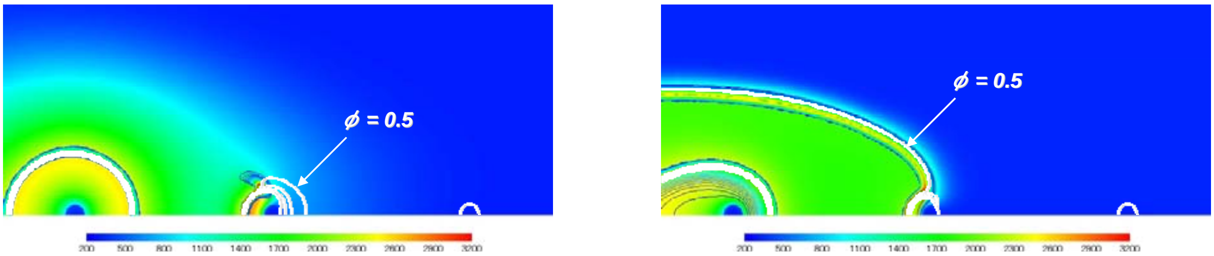


Fig.1 Calculation domain

(a) $\phi_g = 0$ (T = 300 K) (b) $\phi_g = 0.7$ (T = 324 K)

Fig.2 Contours of temperature (gray scale), reaction rate (gray lines), and equivalence ratio (white lines) around spreading flame (d_0 = 1 mm, S = 2 mm).



(a) $\phi_g = 0$ (T = 300 K) (b) $\phi_g = 0.7$ (T = 324 K)

Fig.3 Contours of temperature (gray scale), reaction rate (gray lines), and equivalence ratio (white lines) around spreading flame (d_0 = 1 mm, S = 12 mm).

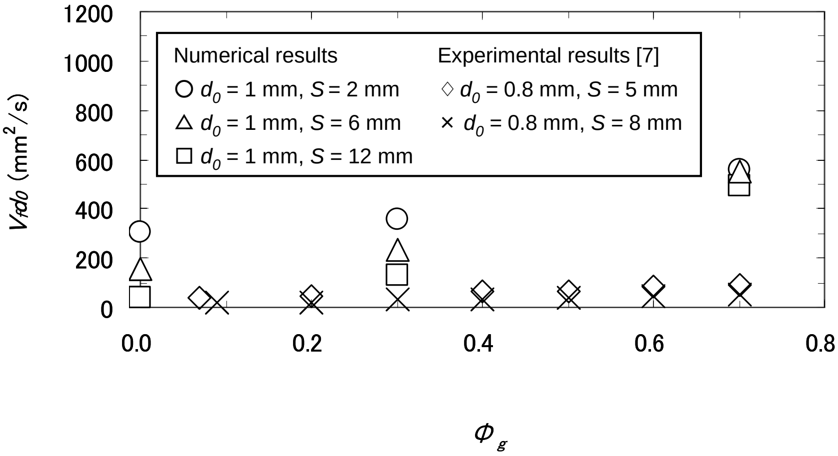


Fig.4 Flame spread rate V_f normalized by d_0 as a function of gas-phase equivalence ratio ϕ_g for numerical simulations in this study and microgravity experiments by Suganuma et al. [7].