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P26

液滴干渉がランダム分散液滴群の燃え広がりに与える影響のパーコレーションモデルによる調査

Study of effects of droplet interaction on the flame spread over randomly distributed droplet clouds using a percolation model

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1. Introduction

The stable combustion of spray combustors requires the flame to spread to the fuel spray and group-combustion excitation. Group combustion is the burning state in which a number of droplets burn with a group flame surrounding them. However, the flame spread and group-combustion-excitation mechanisms have not yet been completely clarified. As a fundamental research for spray combustion, the droplet-combustion experiments have been conducted in microgravity. However, microgravity duration is limited in the ground-based facilities, so, it is difficult to conduct the flame-spread experiments of large-scale droplet clouds in microgravity. Therefore, there is a gap between droplet combustion and spray combustion. In order to bridge the gap, some researchers applied percolation theory to simulate the flame-spread behavior in randomly distributed droplet clouds[1-3]. Saputro[3] conducted a percolation calculation of flame-spread behavior and group-combustion excitation in randomly distributed droplet clouds considering an extreme case with very strong two-droplet interaction and its flame-spread-limit distance $2^{1/3}(S/d_0)_{limit}$ from an imaginary droplet representing the center of two interactive droplets.

Yoshida et al.[4] conducted flame-spread experiments aboard Kibo on ISS and researched the flame-spread limit distribution around interactive droplets in detail using various arrangements of droplet-cloud elements. This study researched the effect of two-droplet interaction on the flame spread over randomly distributed droplet clouds using a percolation model considering the results of flame-spread-limit distribution reported by Yoshida et al. [4]

2. Calculation model

Percolation theory describes particle connection characteristics in randomly distributed particles. When the percolation theory is applied to the flame spread over randomly distributed droplets, the droplet is described as the particle, the flame spread between droplets is described as the particle connection, and the group combustion is described as the large-scale cluster[2]. In the site percolation, particles are connected when particles are in an adjacent lattice point, but in spray combustion, there is no lattice. So, the flame spreads to the next droplets which exist within the flame-spread-limit distance, but the flame cannot spread to the next droplets which exist outside the flame-spread-limit distance[2]. This calculation model uses flame-spread time t_f/d_0^2 which was obtained in the microgravity experiments conducted by Mikami et al.[5] Figure 1 shows the calculation model and the flame-spread calculation procedure with two-droplet interaction. The calculation procedure is as follows:

(1) Arrange droplets on a 2D lattice randomly. The droplets on the bottom side of the lattice are first ignited.
(2) Ignite the next droplet within the flame-spread-limit distance without droplet interaction, FSL1 = $(S/d_0)_{limit}$ = 13.7. Calculate the flame-spread time t_f/d_0^2.

(3) Find the droplet which is ignited next, then calculate the interactive droplet distance S_{BA}/d_0. Determine the position of the imaginary droplet with twice the mass in the midway between two interactive droplets and calculate the flame-spread-limit distance from the imaginary droplet. To calculate the flame-spread-limit distance from imaginary droplets, use the following equation which is derived based on the results of the microgravity experiments [4].

$$(S_{M2L}/d_0)_{limit} = FSL2\{1\text{-}0.28\exp(\text{-}\{FSL1\text{-}(S_{BA}/d_0)\}/2)\}, \text{ where } FSL2 = 2^{1/3}FSL1. \quad (1)$$

(4) The calculation procedure is repeated until the flame cannot spread to the next droplets or the flame reaches all the sides of the lattice.

When calculating without droplet interaction, the calculation order is (1), (2), and (4). The calculation was conducted for 1000 different patterns of droplet arrangement for each mean droplet spacing $(S/d_0)_m$. Here, the mean error of occurrence probability of group combustion when the occurrence probability of group combustion of 50% is 1.58%. In this study, the appearance of group combustion is defined as the case in which the flame reaches all side of the lattice.

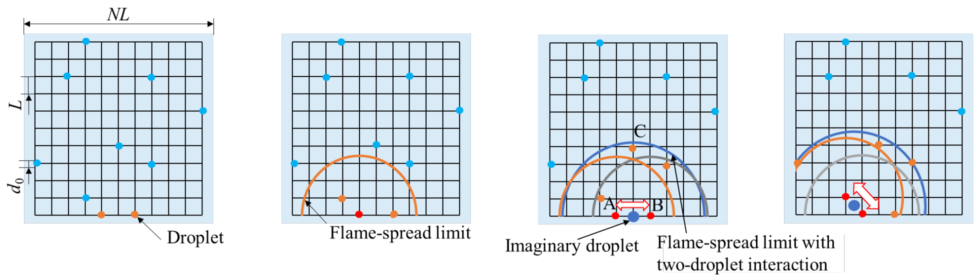

Fig. 1 Calculation model and the flame spread calculation procedure with two-droplet interaction.

3. Results and discussion

Figure 2 shows the comparison of occurrence probability of group combustion without and with two-droplet interaction against mean droplet spacing. As the mean droplet spacing $(S/d_0)_m$ increases, the occurrence probability of group combustion rapidly decreases around a specific value of mean droplet spacing $(S/d_0)_m$. In order to predict the threshold value of mean droplet spacing $(S/d_0)_m$, we define the mean droplet spacing $(S/d_0)_m$ for the occurrence probability of group combustion of 50% as the critical mean droplet spacing $(S/d_0)_{critical}$. In the case without droplet interaction with $NL/d_0 = 600$ and $L/d_0 = 2$, the critical mean droplet spacing $(S/d_0)_{critical}$ is 11.15, and in the case with two-droplet interaction with $NL/d_0 = 600$ and $L/d_0 = 2$, the critical mean droplet spacing $(S/d_0)_{critical}$ is 12.09. The critical mean droplet spacing $(S/d_0)_{critical}$ without two-droplet interaction is larger than that without droplet interaction. This is because the flame-spread-limit distance with two-droplet interaction becomes larger, so the flame can spread to more next unburned droplets.

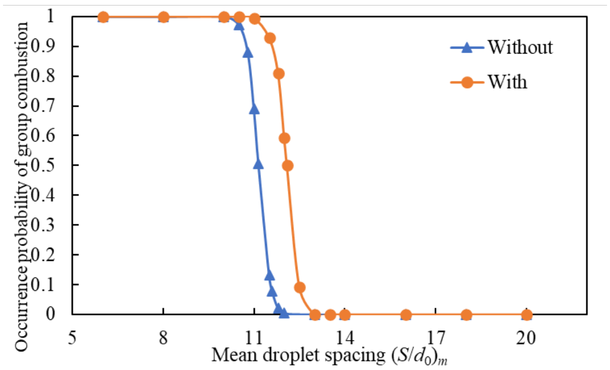

Fig. 2 Comparison of occurrence probability of group combustion on mean droplet spacing without and with two-droplet interaction. ($NL/d_0 = 600$, $L/d_0 = 2$)

To research the burned droplets which are affected only by two-droplet interaction, we investigate the burned droplets which are affected only by imaginary droplets. For example, the flame spreads to Droplet C in Figure 1(3) only by the effect of the imaginary droplet. Figure 3 shows the portion of mean burned droplets affected only by imaginary droplets to the total number of droplets. As Fig. 3 shows, the portion of mean number of burned droplets affected only by two-droplet interaction shows a large value within a specific range of mean droplet spacing and attains maximum value at the mean droplet spacing bit greater than the critical mean droplet spacing without droplet interaction. The critical mean droplet spacing $(S/d_0)_{critical}$ becomes larger by the effects of such two-droplet interaction.

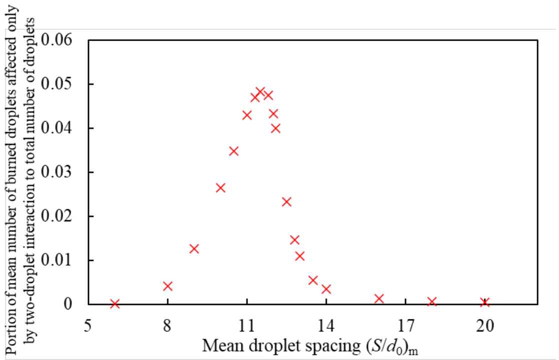

Fig. 3 Portion of mean number of burned droplets affected only by two-droplet interaction to total number of droplets vs. mean droplet spacing. (NL/d_0 = 600, L/d_0 = 2)

To observe the effect of droplet interaction on flame-spread behavior, we calculated flame spread with and without two-droplet interaction for the same droplet arrangement. Figure 4 shows the flame-spread behavior without droplet interaction in a droplet arrangement with $(S/d_0)_m$ = 11.15, which is the critical mean droplet spacing without droplet interaction. Figure 5 shows the flame-spread behavior with two-droplet interaction in the same droplet arrangement as in Fig. 4. As shown in Fig. 4, the flame-spread behavior is complicated in the critical condition, but as shown in Fig. 5, the effect of two-droplet interaction makes the flame spread uncomplicated unlike in Fig. 4. This is because, as shown in Fig. 3, there are burned droplets which are affected only by two-droplet interaction, and furthermore the flame spread continues from these burned droplets. For this reason, even though the droplet arrangements of Figs. 4 and 5 are the same, the flame-spread behavior is different.

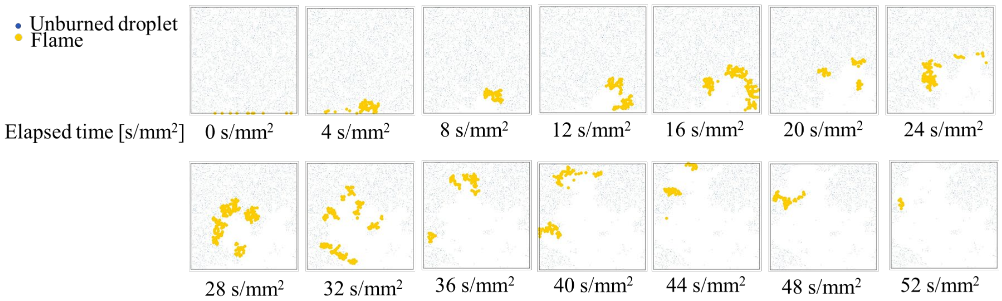

Fig. 4 Flame-spread behavior without two-droplet interaction for the same droplet arrangement as in Fig. 5. (NL/d_0 = 600, L/d_0 = 2, $(S/d_0)_m$ = 11.15)

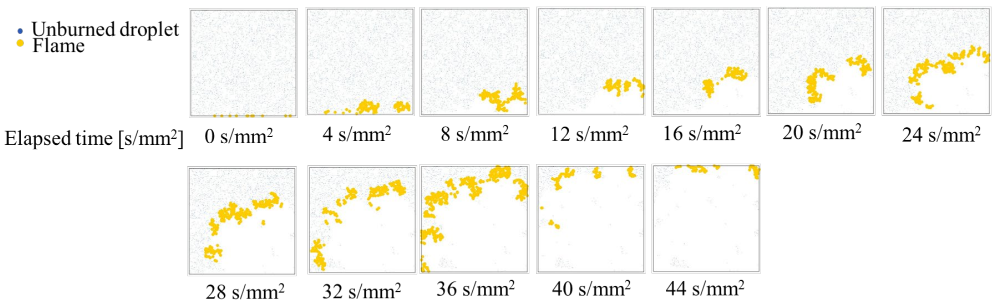

Fig. 5 Flame-spread behavior with two-droplet interaction for the same droplet arrangement as in Fig. 4. (NL/d_0 = 600, L/d_0 = 2, $(S/d_0)_m$ = 11.15)

Mikami et al.[6] performed the microgravity experiments of flame spread over randomly distributed droplet clouds aboard the ISS and reported that the mean droplet spacing at the group-combustion excitation limit is between 15.2 and 16.1. However, the critical mean droplet spacing with two-droplet interaction obtained in this study is smaller than the result of the experiments conducted by Mikami et al.[6]

Mikami et al.[7] reported that near the group-combustion-excitation limit for the flame spread over randomly distributed droplet clouds, the large-scale ignition phenomenon was observed. They stated that the large-scale ignition phenomenon is caused by the ignition of a flammable mixture generated by heating multiple droplets existing outside the local flame-spread limit, and there is a possibility of a cool-flame appearance in this phenomenon.

In this study, we only considered two-droplet interaction for the enhancement of the flame-spread-limit distance. For this reason, the critical mean droplet spacing with two-droplet interaction obtained in this study is smaller than the result of the experiments conducted by Mikami et al.[6] As a future work, it is necessary to simulate the flame-spread behavior with the pre-vaporization and a cool-flame.

4. Conclusions

This study researched the effect of two-droplet interaction on the flame spread over randomly distributed droplet clouds using a percolation model which the flame-spread-limit distance varies with distance of interactive droplets. The main findings are as follows:

(1) The critical mean droplet spacing with two-droplet interaction becomes large because the flame spread continues from burned droplets affected only by two-droplet interaction.

(2) As a future work, it is necessary to simulate the flame-spread behavior with pre-vaporized and a cool-flame.

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