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二液滴・三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二次元パーコレーションモデルによる調査

Study of effects of two-droplet and three-droplet interaction on the flame spread over randomly distributed droplet clouds using a two-dimensional percolation model.

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1. Introduction

In order to obtain the stable combustion of fuel spray, it requires the flame spreading 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 clarified. As fundamental research for spray combustion, the droplet-combustion experiments have been conducted in microgravity environment in ground-based facilities, where the microgravity duration is limited. For this reason, it is difficult to conduct the flame spread experiments of large-scale droplet clouds in microgravity, and it makes a gap between droplet combustion and spray combustion. In order to bridge this gap, some researches used percolation model to simulate the flame-spread behavior in randomly distributed droplet clouds1), 2). Saputro3) conducted a percolation calculation of flame-spread behavior in randomly distributed droplet clouds considering two-droplet interaction. Yoshida et al. 4) conducted flame-spread experiments aboard Kibo on the International Space Station (ISS) and researched the flame-spread limit distribution around two interactive droplets and three interactive droplets in detail using various arrangements of droplet-cloud elements. This study researched the effect of three-droplet interaction on the flame spread over randomly distributed droplet clouds at the critical point of the case with two-droplet interaction 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 on a lattice. When the percolation theory is applied to the flame spread over randomly distributed droplets clouds, 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 cluster2). Particles are connected when particles are in adjacent lattice point in the site percolation, but there is no lattice in spray combustion. So, in this percolation model, the flame spreads to the droplets which exist within the flame-spread-limit distance2). 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 calculation procedure with three-droplet interaction. The calculation procedure of three-droplet interaction is as follows:

(1) Arrange droplets on a 2D lattice with the size of $NL/d_0 \times NL/d_0$ randomly. The droplets on the bottom side of the lattice are first ignited.

(2) Calculate the flame spread without droplet interaction. Ignite droplets which exist within the flame-spread-limit distance FSL1 = $(S/d_0)_{\mathrm{limit}} = 13.7$. Calculate the flame-spread time t_f/d_0^2.

(3) Calculate the flame spread with two-droplet interaction. 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 $(S_{M2L}/d_0)_{\mathrm{limit}}$. To calculate the flame-spread-limit distance from imaginary droplet, we used the equation which is derived based on the results of microgravity experiments conducted by Yoshida et al.4)

(4) Calculate the flame spread with three-droplet interaction. Find three droplets which interact each other, then calculate the interactive droplet distance. Determine the position of the imaginary droplet with three times the mass in the center of mass of three interactive droplets and calculate the flame-spread-limit distance from the imaginary droplet $(S_{M3L}/d_0)_{\mathrm{limit}}$. To calculate the flame-spread-limit distance from imaginary droplet, we used the equation which is derived based on the results of microgravity experiments conducted by Yoshida et al.4)

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

For the calculation without droplet interaction, the calculation order is (1), (2) and (5). For the calculation with two-droplet interaction, the calculation order is (1), (2), (3) and (5). The calculation with two-droplet interaction was conducted for 1000 different patterns of droplet arrangement for each mean droplet spacing $(S/d_0)_m$. In this study, the appearance of group combustion is defined as the case in which the flame reaches all sides of the lattice.

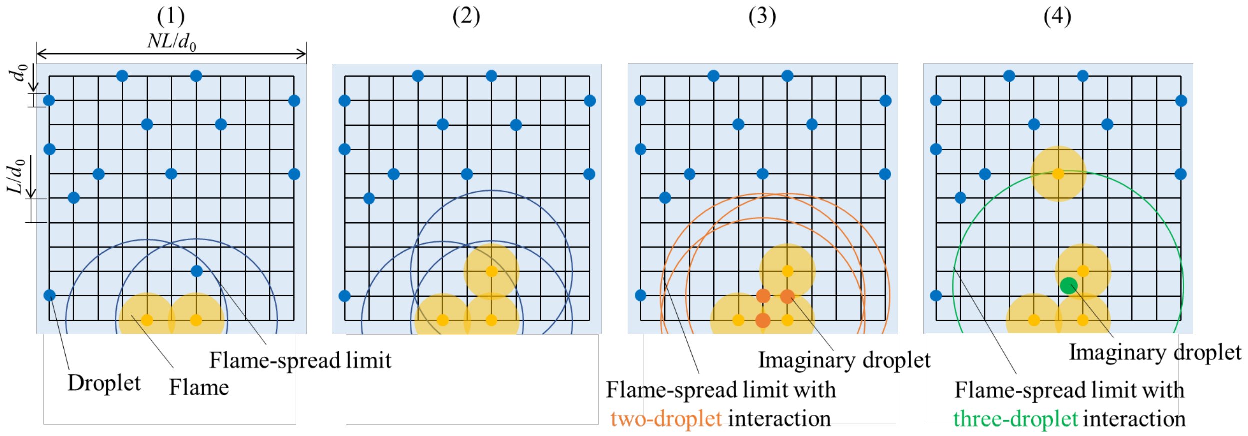

Figure 1. Calculation model and calculation procedure with three-droplet interaction.

3. Results and discussion

With two-droplet interaction, in the lattice with lattice size of 600 and a lattice point interval of 2, the critical mean droplet spacing is 12.09.[6] In order to research the effect of three-droplet interaction on the flame spread over randomly distributed droplet clouds at the critical point of the case with two-droplet interaction, we employed two typical droplet arrangements: (1) Droplet arrangement in which the time for the flame to reach the top side of the lattice becomes average. (2) Droplet arrangement in which the time for the flame to reach the top side of the lattice becomes maximum. Figure 2 shows the flame spread behavior for the droplet arrangement in which the time for the flame to reach the top side of the lattice becomes average. In these figures, the blue circles mean unburned droplets, the yellow circles mean the flames which are not affected by droplet interaction, the orange circles mean the flames affected only by two-droplet interaction, and the green circles mean the flames affected only by three-droplet interaction. There are the droplets that are ignited faster because of the effect of three-droplet interaction, but the flame spread behaviors are almost the same for the case only with two-droplet interaction and the case with three-droplet interaction.

Figure 3 shows the flame spread behavior for the droplet arrangement in which the time for the flame to reach the top side of the lattice becomes maximum. In this case, the flame spread behavior with three-droplet interaction is different from that with two-droplet interaction. After 70 s/mm^2 in the case with three-droplet interaction, the effect of three-droplet interaction makes flame spread radially from the center of the lattice. In the case only with two-droplet interaction, the flame-spread behavior is more complicated and it takes more long time to finish the flame spread.

From Figs. 2,3, there are droplets affected by three-droplet interaction, but in the case of droplet arrangement in which the time for the flame to reach the top side of the lattice becomes average does not change flame-spread behavior. Therefore, the effect of three-droplet interaction at the critical point seems to be small. However, in the case with three-droplet interaction, burned droplets increases about by 5% as compared with the case only with two-droplet interaction. As a future work, it is necessary to calculate the critical mean droplet spacing with three-droplet interaction.

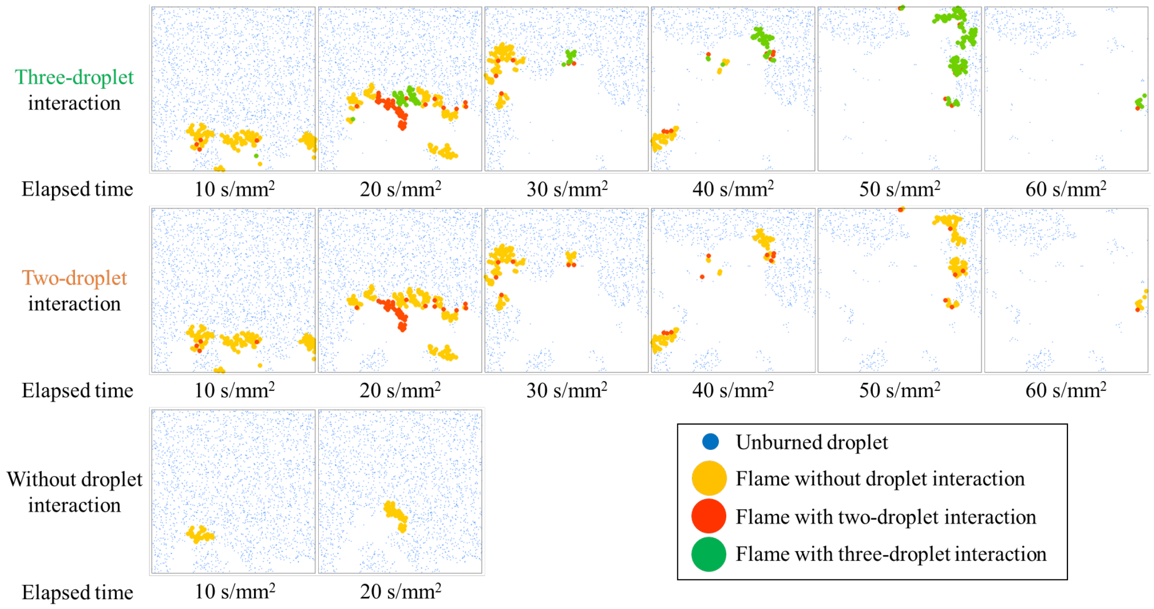

Figure 2. Flame spread behavior for a droplet arrangement in which the time for the flame to reach the top side of the lattice becomes average. ($NL/d_0 = 600$, $L/d_0 = 2$, $(S/d_0)_m = 12.09$)

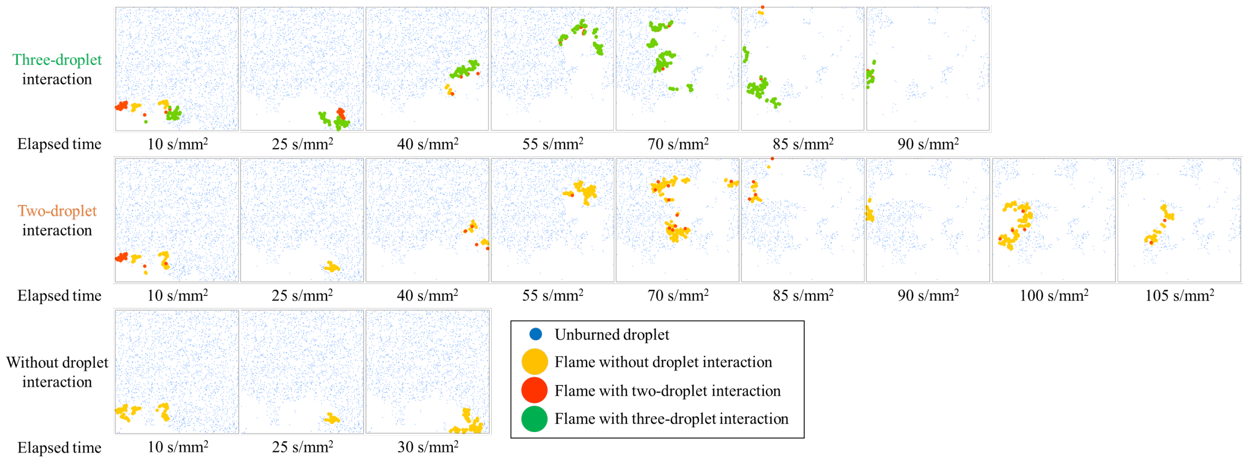

Figure 3. Flame spread behavior for a droplet arrangement in which the time for the flame to reach the top side of the lattice becomes maximum. ($NL/d_0 = 600$, $L/d_0 = 2$, $(S/d_0)_m = 12.09$)

4. Conclusion

This study researched the effect of three-droplet interaction on the flame spread over randomly distributed droplet clouds at the critical point of the case with two-droplet interaction using a percolation model which the flame-spread-limit distance varies with distance of interactive droplets.

In the case of a droplet arrangement in which the time for the flame to reach the top side of the lattice becomes average, the flame-spread behavior seems not to change significantly even if we consider three-droplet interaction. In the case with three-droplet interaction, however, burned droplets increases about by 5% as compared with the case only with two-droplet interaction. It is necessary to calculate the critical mean droplet spacing with three-droplet interaction as a future work.

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