Influence of Drop Spacing on Burning of an Emulsified-Drop Stream

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Abstract

Combustion characteristics of water-in-dodecane emulsion drops with various initial spacings were studied experimentally by using a free-falling drop burning apparatus. The initial drop spacings (S_i) were 2.5, 5, 10, 40, 75 (70), 100. S_i (s/d_i) was defined as the ratio of the drop center-to-center distance (s) to the initial drop diameter (d_i). The water content (β) and the oxygen concentration (Ω_{O2}) were fixed at 5% and 21%, while two drop sizes 550 μm and 450 μm were compared. The results showed that the transition of the drop flame occurred for all cases in the experiment. For $S_i > 10$ along the flow direction, the flame around the drops would change from a blue spherical flame to a yellow flame and a wake flame, and the drop flame extinguished later in the downstream region. Soot particles was generated and drops collision and merging occurred to form a flame tube for S_i =2.5 in both cases of d_i = 550 μm and 450 μm. Besides, drop expansion was observed in both cases of d_i = 550 μm and d_i = 450 μm, while micro-explosion only occurred in the far downstream region for S_i = 40, d_i = 450 μm. It was also shown that the emulsion drop evaporation rate was not a constant, and the trend of the drop evaporation rate was strongly influenced by changing the initial drop size.

Introduction

Spray combustion has been widely used in industrial applications especially in internal combustion engines and steam turbines. Its burning characteristics were controlled by the drop size and the drop evaporation efficiency in the combustion chamber. There were some factors influencing the evaporation efficiency, for example, the drop size, the combustion environment, the interactions of the drops, and the fuel characteristics. Emulsified fuel was widely used in the combustion chamber. There are two advantages of introducing water into the combustion reaction: (1) Water reduces the formation of soot and NO_X; (2) Emulsified fuel induces micro-explosions, which is enhances atomization [1-4].

There has been extensive research of the emulsion fuel drops up to the present. Avedisian and Anders's research [5] showed that the micro-explosion of an emulsified fuel drop occurred if the superheat limit of the fuel/water emulsion was less than the boiling point of the fuel. Wang and Law [6] studied emulsion drops freely fell into a hot, oxidizing, high pressure environment with a pressure up to 5 atm. Results showed that increasing pressure not only enhanced the possibility of micro-explosion of an otherwise non-explosive mixture, but also advanced its occurrence during the drop lifetime. Later, an experimental investigation [7] was conducted on the combustion characteristics of drops of *n*-heptane, *n*-decane, *n*-dodecane, *n*-hexadecane and iso-octane emulsified with various amount of water. The drop burning time could be significantly reduced through judicious fuel blending so as to minimize the ignition delay and advanced the onset of micro-explosion.

It was known that the micro-explosion of the emulsion drop occurred when the boiling point of the external oil layer was higher than the internal water superheating limit. When the emulsion drop was in the combustion process, the internal small water drops would evaporate due to homogeneous nucleation, and expand the emulsion drop into fragmentation, which was known as the "second atomization". Homogeneous nucleation of the emulsion drop occurred randomly, therefore there have been some research analyzing the micro-explosion phenomenon by the Weibull distribution [3, 8-10].

Tsue et al. [8, 9] suggested that micro-explosion was a random process, and thus they used statistics to analyze micro-explosion probability. Their results showed that micro-explosion probability increased with increasing water content. The same analysis was used to show that the distribution of the average waiting time was not influenced by gravity.

Kadota et al. [3, 10] studied the micro-explosion of emulsion drops on a hot surface. The base fuel oil, initial water content, environmental pressure, and surface temperature affected the number of micro-explosions and waiting time. An increase in the initial water content decreased the waiting time.

The micro-explosion waiting times were in the order: hexadecane> tetradecane > dodecane > decane. Research results on micro-explosion of emulsion drop have been mostly observatory or statistical. Deterministic prediction of micro-explosion is by far impossible.

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When the emulsified fuel was in the process of spray combustion, there was not only the phenomenon of micro-explosion but also the interaction between the drops. Concerning the drop interaction in the spray combustion process, many researchers simplified the spray combustion situation to a drop string to observe interaction between the drops.

In the references [11-14], drop spacings ranging from hundreds of drop diameters to slightly less than two diameters were studied by various researchers. The interaction effects became increasingly more important for small drops. For a drop spacing of less than 2 droplet diameters, the life-time of the drop is more than twice the life-time of an isolated drop. It was also known that when the drop spacing decreased, the effect of drop interaction became significant and the combustion time lengthened because of lower evaporation rate. This phenomenon was thought to be affected by the heat and mass transfer between the interacting drops [15]. Nevertheless, in some researches, it was observed that if the spacing of drop was in a certain range, the evaporation rate was higher than that of an isolate a drop. [1, 2, 16-20].

In most of the studies on drop interaction, pure fuel was usually used in the researches. The researches about emulsion drops were usually focused on single drops, and the experimental investigation of the streamwise interaction of burning emulsion fuel drops with natural convection considered was very rare. Therefore, in this research, a free falling drop string entering a high-temperature oxygen environment was observed for the characteristics of the drop string flame, the micro-explosion, and the diameter variation of the drops.

Experimental Apparatus

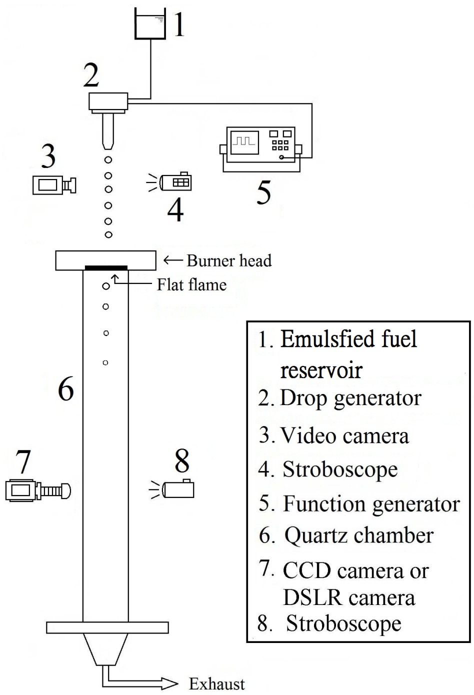

Figure 1 Experimental apparatus.

Figure 1 shows the schematic of the experimental apparatus. A string of drops of water-in-dodecane emulsion with various initial spacing were injected into a high-temperature environment to study the characteristics of the flame width, the diameter variation of the drops, and the micro-explosion as the drops reached different locations in the combustion chamber.

Emulsified fuel was produced by the following procedure. A quantity of surfactant (Span80 volume fraction of 3%) was added to the pure dodecane, and stirred by a homogeneous mixer for one minute. Then water 5% volume fraction was added into the mixture of dodecane and surfactant, and stirred for five minutes to make the water-in-dodecane emulsion. In the process, the speed of homogeneous mixer was set at 9000 rpm. Finally, the water-in-dodecane emulsion was placed in the reservoir.

The drop generation system comprised a reservoir, a drop generator, a stroboscope, a video camera and a function generator. The drop generator was driven by the signal from a function generator. By controlling the vibrating frequency of the piezoelectric plate, stable drop strings with uniform size and a specified spacing could be produced. The initial drop spacings (S_i) were 2.5, 5, 10, 40, 75 (70) and 100. S_i (s/d_i) was defined as the ratio of the drop center-to-center distance (s) to the initial drop diameter (d_i). In this study, the initial drop diameter was fixed at either 550 μm or 450 μm. The drop velocity varied from 2.4 m/s at x = 9 cm to 4 m/s at x = 50 cm and the gas velocity varied from 2.5 m/s at x = 15 cm to 2.25 m/s at x = 50 cm [20].

The combustion system consisted of a combustion chamber (quartz tube), an image acquisition system and an exhaust system. The quartz tube had a diameter of 46 mm, a thickness of 2 mm and a length of 1000 mm. In the combustion chamber, a flat flame at the top of the quartz tube was used to create the high gas temperature environment inside the quartz tube. The flat flame was formed by a premixed gas of methane and air/oxygen. After igniting the flat flame, the exhaust system was turned on for about 20~30 minutes to make sure all the systems became stable. A 4 mm hole in the center of the flat flame system allowed the drops to fall into the quartz chamber to be burned. In this study, the oxygen concentration (Ω_{O2}) inside the quartz tube was controlled at 21%. The volumetric flow rates of air, oxygen and methane were 323 ml/s, 86 ml/s, and 31 ml/s respectively. The axial temperature distribution inside the combustion chamber was measured by inserting an R-type thermocouple alone the centerline of the quartz tube. The temperature decreased from about 900^{o}C to 400^{o}C with axial position (x).

The drop sizes were photographically determined by using the strobe lighting synchronized with the CCD camera to capture the instantaneous images of the burning drop in different positions. Furthermore, a DSLR camera was used to capture the images of the burning drop string.

Results and Discussion

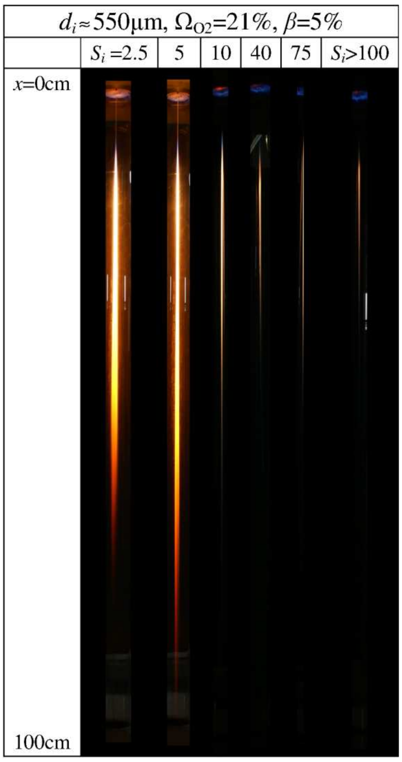

Figure 2 Burning drops string of various initial drop spacing (d_i = 550 μm).

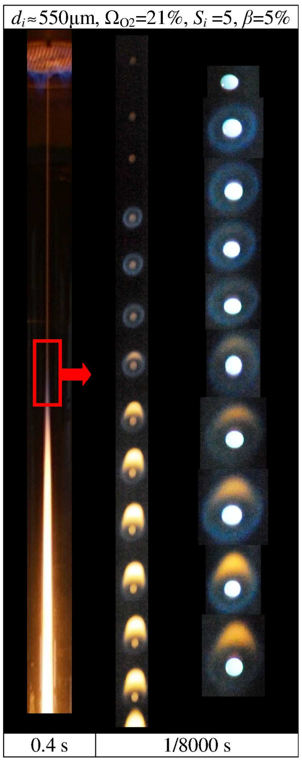

Figure 3 Ignition and flame transition process of drop string.

Figure 4 Image of emulsion drop expansion.

Figure 2 shows the direct photographs of the burning drop strings of different initial drop spacings (S_i = 2.5, 5, 10, 40, 75, and 100). These photos were taken by DSLR camera with shutter 0.4s, aperture 5.3 and ISO 100. When the drops entered the high temperature environment, they needed some time to evaporate before they were ignited. Therefore the drop string was ignited at a distance from the burner head. An ''ignition point'' could be identified for each flame streak in Fig. 2. The ignition point of drop string did not change significantly when S_i was varied. Furthermore, in some researches, it was shown that the ignition point or delay time of the emulsion drops was farther than the pure drops. The reason was that the water in the emulsion drop absorbed heat to cause ignition delay [7, 22].

Figure 3 shows the ignition and flame transition process of drop string. The ignition point of the drop string and the flame string could be cleanly observed when the shutter was set at 0.4s. However, the instantaneous image of the drop flame in the falling process could not be seen. If the shutter was changed to1/8000s, with the stroboscopic lighting, the instantaneous image of the drop flame in the falling process could be seen clearly. In this study, a spherically flame was clearly shown at the ignited point of drop string. At the position, the drop velocity might be slightly smaller than the ambient gas velocity, and the small downward flow convection caused by the difference of drop and gas velocity here in was just balanced with the small upward nature convection [20]. Therefore, the drop was enveloped by a spherical flame. As the drop moved downstream, the drop velocity exceeded the gas convection and the drop flame moved behind the drop gradually. Due to the gas convection, the fuel vapor flowed behind the wake region of the drop, so the drop flame changed from a blue spherical flame to a yellow wake flame. The ignition points and the early flame transformation process for different initial spacing cases were similar. Nevertheless, the interaction between the drops was stronger for the small S_i cases as the drops moved to the downstream, and it was observed that the drop flame would merge and form a bright yellow flame tube. The width of the bright yellow flame tube for a smaller S_i was wider than that for $S_i > 100$, and the drop string evaporated and burned in the flame tube.

From figure 2, it could be found that the flame length of $S_i = 2.5$ was shorter than that of $S_i = 5$ and the flame length decreases with increasing S_i ($\geqq 5$). The reason that the flame length of $S_i = 2.5$ was shorter than that of $S_i = 5$ was that some burning drops in the drops string collided and merged in the $S_i = 2.5$ case and this caused water content, drop spacing and drop size variation. The increase of drop spacing due to drop collision influence the drop evaporation rate, so that the flame for $S_i = 2.5$ would extinguish earlier.

As S_i increased ($S_i \geqq 10$), the interaction between the drops decreased, so the flame width and flame length also decreased. The flame around the drops would change from a blue spherical flame to a yellow flame and a wake flame, and the drop flame extinguished later in the downstream region. It was not observed that there were any soot particles generated, or there was flame merging to form a flame tube.

Figure 2 shows no micro-explosion of emulsion drop. It was supposed that the quartz tube was too short to have enough time to heat the drop, the drop size was too big and the water content was insufficient to cause micro-explosion, but the phenomenon of drop expansion could be observed for $S_i \geqq 5$. Figure 4 shows the expansion of the emulsion drops. This picture was taken by CCD camera with stroboscopic lighting. By the stroboscope, repeated exposures of the same drop were taken, and the expansion of the drop could be seen clearly.

As the emulsion drop was heated in the combustion chamber, the heat would transfer from the surface into the drop center. There were many heterogeneous water drops dispersing in the emulsion drop, when the water drop temperature reached a certain temperature, water vapor could be generated and the vapor would cause the emulsion drop to expand. However, to cause the micro-explosion it needed more water vapor.

In order to know if the micro-explosion would occur, the ambient temperature, water content, and the heating time were all fixed, but the drop size was changed for 450 μm to be the comparison, which would be discussed in the following figures.

In this study, the water content and the oxygen concentration were fixed at 5% and 21% respectively, but the drop size was changed to 450 μm to compare with the case of $d_i = 550$ μm. Figure 5 shows the direct photographs of the burning drop strings of different initial drop spacings ($S_i = 2.5$, 5, 10, 40, 70, and 100). The flame width and length were all shorter and weaker than the case of $d_i = 550$ μm. Similarly, the flame length of $S_i = 2.5$ was shorter than $S_i = 5$, and some burning drops in the drops string collided and even merged at $S_i = 2.5$ from the CCD images. It was also observed that soot particles were generated and drop flame merged together to form the flame tube, which was similar to the case of $d_i = 550$ μm. For $10 < S_i < 100$, the flame variation was almost the same, and no drops collision, soot layer generation, or the drop flame merging were observed. However, there was a phenomenon of micro-explosion for $S_i = 40$ case.

Figure 6 shows a clearer image of the micro-explosion. The left image shows the flame without micro-explosion, and the flame color changed from yellow to blue. However, in the right image, it can be clearly seen there was a flame of successive micro-explosion at $x \cong 60$ cm, and the color of the micro-explosion flame was reddish.

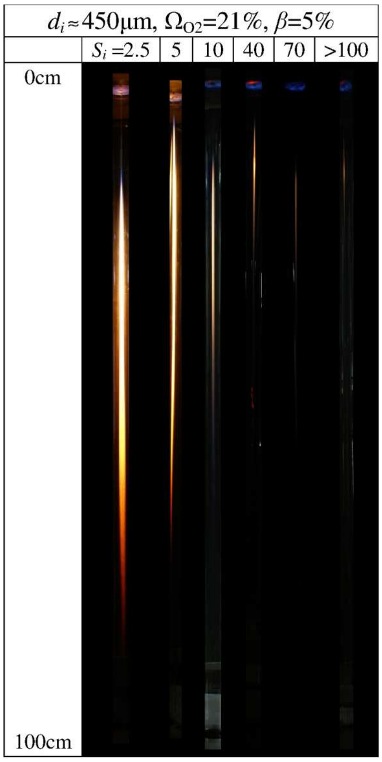

Figure 5 Burning drops string of various initial drop spacing (d_i = 450µm).

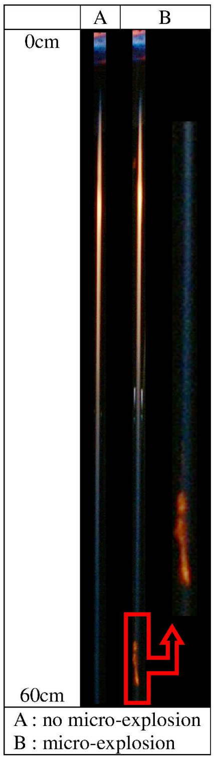

Figure 6 The image of the micro-explosion flame.

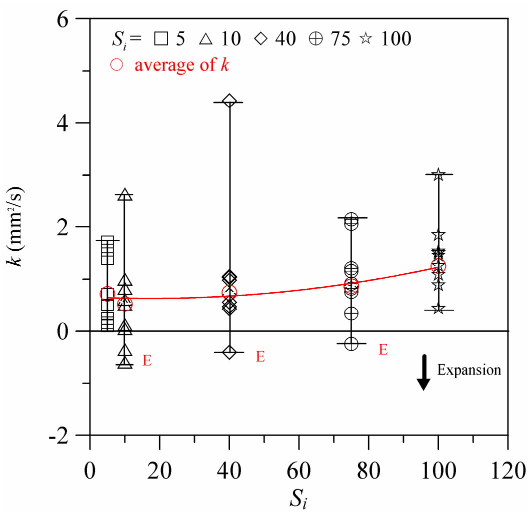

Figure 7 Average evaporation rate constant (k) at different initial drop spacing (d_i = 550 µm).

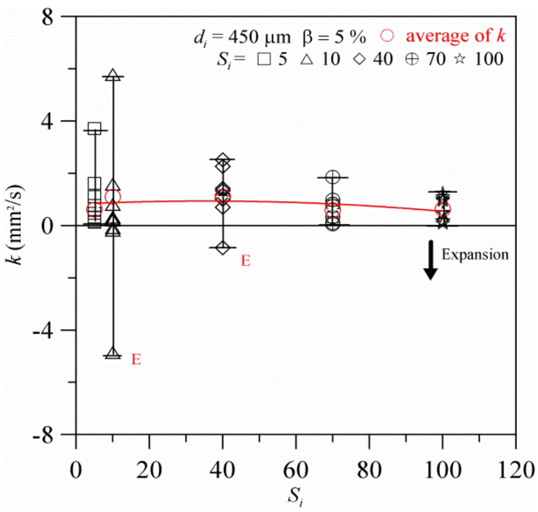

Figure 8 Average evaporation rate constant (k) at different initial drop spacing (d_i=450 µm).

To further investigate the burning behavior of the drop in a burning string, the variations of evaporation rate constant (k) of drop with time for different initial drop spacing were calculated and shown in Fig. 7. The evaporation rate constant (k) was defined as $k = (d^2_{so}-d^2_s)/t$, where d_{so} was the initial diameter of the drop, d_s was the diameter of the drop at time t, and t was the time as the diameter of drop varied from d_{so} to d_s.

The emulsion drops vaporized in the combustion process, so the drop size would gradually become smaller along the x positions. The data in figure 7 was the drop evaporation rate calculated in each x position. However, due to the drop expansion, the evaporation rate constant (k) could not stay as a constant and the drop evaporation rate (k) would have a negative value, so it was marked "E" to indicate the drop expansion. Finally, the averaged evaporation rate constants (k) were calculated to show the trend of the evaporation rate It was found that the average evaporation rate increased as S_i increased for the case of $d_i = 550$ μm.

Figure 8 shows the average evaporation rate constant (k) for different initial drop spacings of the case $d_i = 450$ μm. Obviously, the variation of the average evaporation rate constant (k) was very different from the case of $d_i = 550$ μm, but it was similar to the result of research [20]. The average evaporation rate constant (k) decreased with S_i for $S_i < 10$, and for $S_i = 40$, it was larger than that of an isolated drop. Besides, the micro-explosion was only found in the case of $d_i = 450$ μm, as it was supposed that the drop had a better heat transfer condition for the case of $S_i = 40$ than the other cases.

Summary and Conclusions

1. For $S_i > 10$ along the flow direction, the flame around the drops would change from a blue spherical flame to a yellow flame and a wake flame, and the drop flame extinguished later in the downstream region. For $S_i = 2.5$ or 5, the flame of burning drops would merge to form a flame tube.
2. The drop expansion was observed in both cases of $d_i = 550$ μm and $d_i = 450$ μm, while micro-explosions only occurred in the far downstream region for $S_i = 40$ and $d_i = 450$ μm case.
3. The emulsion drop evaporation rate was not a constant. It was noted that the initial drop size plays an important role in affecting the evaporation rate.

Acknowledgements

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