Observation of droplet behavior of emulsified fuel in secondary atomization in flame

Hirotatsu WATANABE*, Yutaka SHOJI*, Takuma YAMAGAKI**, Jun HAYASHI**, Fumiteru AKAMATSU** and Ken OKAZAKI*

*Department of Mechanical and Control Engineering, Tokyo Institute of Technology
2-12-1-16-7 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
E-mail: watanabe.h.ak@m.titech.ac.jp

**Department of Mechanical Engineering, Osaka University
2-1 Yamadaoka, Suita-shi, Osaka 565-0871, Japan

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Abstract
The study aims to visualize droplet behaviors of emulsified fuel in secondary atomization in a flame stabilized in a laminar counterflow field. To study secondary atomization characteristics in the flame, direct photography of the flame using a color high-speed video camera (7,000 fps) and magnified shadow imaging of spray droplets using a monochrome high-speed video camera (180,064 fps) were used. Frequencies of secondary atomization in the flame were also discussed. As a result, “bright spots,” which were of similar or higher luminosity than the surrounding area were observed by direct photography around the luminous flame of the emulsified fuel, whereas the frequency of occurrence of “bright spots” was almost negligible when n-dodecane was used. Observations indicated that the droplet flame rapidly expanded. This expansion was linked to secondary atomization phenomena such as puffing (i.e., vapor eruption from the droplet surface), partial micro-explosion (i.e., where a large portion of a droplet bursts), and micro-explosion (i.e., where the entire droplet bursts), which were visualized in the flame by magnified shadow imaging. It was suggested that secondary atomization caused rapid evaporation and spread of fuel vapor. The magnified shadow imaging technique provided a clear description of droplet behavior in the flame. Numerous puffing and micro-explosion were observed regardless of the flame emissions. In addition, it was observed that vapor blowout in secondary atomization accelerated droplet velocity, and led to the random movement of spray droplet. It was shown that the frequencies of secondary atomization increased in the downstream region where the luminous flame was formed. Secondary atomization occurred in droplets of various sizes in the downstream region, whereas it occurred in only small droplets in the upstream region where the luminous flame was not formed.

Key words: Emulsified fuel, Secondary atomization, Flame, Micro-explosion, Puffing

1. Introduction

There are widespread applications of liquid fuel spray combustion. However, pollutant emissions from spray combustion, such as NO\textsubscript{x} and soot, are serious global problems to be solved. Emulsified fuel is considered to be a possible alternative to reduce the emission of pollutants from practical combustion systems by secondary atomization. Emulsified fuel consists of a base fuel and water with or without a trace content of surfactant. Previous studies have shown that NO\textsubscript{x}, CO, and soot emissions are reduced in spray combustion using emulsified fuels (Ballester, et al., 1996; Kadota and Yamasaki, 2002; Attia and Kulchiskiv, 2014). The occurrence of secondary atomization is the widely accepted explanation for the observed decrease in CO and soot emissions. Secondary atomization in emulsified fuel mainly consists of micro-explosion and puffing (Watanabe, et al., 2009). In micro-explosion, the entire droplet bursts into smaller droplets. In puffing, water vapor erupts from the droplet surface in the form of fine droplets. Because of the interest in puffing and micro-explosion, many researchers have studied these using single droplet experiments (Segawa, et al., 2000; Watanabe, et al., 2009; Watanabe, et al., 2010; Suzuki, et al., 2011; Mura, et al., 2014; Califano,
et al., 2014). The fiber-support technique, used to anchor the droplet (Segawa, et al., 2000; Bae and Avedisian, 2004; Yozgatgil, et al., 2007; Watanabe, et al., 2009; Watanabe, et al., 2010; Suzuki, et al., 2011; Mura, et al., 2014; Califano, et al., 2014), has been used in studies of secondary atomization because it provides considerably useful information regarding, for example, clear droplet behavior. Because nucleation on the surface of the wire used in the fiber-support technique is unavoidable, some researchers have used unsupported techniques (Warnat, et al., 1994; Jackson and Avedisian, 1998; Mikami, et al., 1998).

Single droplet experiments using either fiber-support or unsupported techniques often use droplets with sizes ranging from 200 to 1000 µm, which are much larger than actual spray droplets that have typical sizes of < 100 µm. Even though the size difference affects the droplet heating rate and the waiting time for the observation of secondary atomization, the issue of whether secondary atomization information obtained in large droplet experiments are applicable to spray flow is not well understood. Recently, secondary atomization in spray flow has been extensively studied (Mizutani, et al., 2000; Fuchihata, et al., 2003; Ochoterena, et al., 2010; Watanabe, et al., 2013; Huo, et al., 2014). Ochoterena et al. (2010) studied spray development and combustion by optical methods in an optically accessed combustion vessel under conditions similar in a diesel engine. “Glowing spots,” which were suggested to be caused by micro-explosion were observed in the burning emulsified fuel spray. Similar phenomena were observed in other studies (Mizutani, et al., 2000; Fuchihata, et al., 2003). Huo et al. (2014) observed “bright spots” or “scattered spots” of high luminosity around the central lift-off region in an emulsified diesel spray flame. These “spots” in the spray flame of an emulsified fuel have been reported; however, significant attention has not yet been paid towards visualization of spray droplet behaviors in secondary atomization in the flame, which is necessary to understand the nature of “spots” in a spray flame, and to develop models of secondary atomization. Our previous study has visualized puffing and partial micro-explosion in an emulsified fuel spray flow by shadow imaging under N₂ (Watanabe and Okazaki, 2013); however, little effort was made to visualize droplet behavior during secondary atomization in the flame.

This study aims to visualize droplet behavior of emulsified fuel in secondary atomization in a flame stabilized in a laminar counterflow field. To study secondary atomization characteristics in the flame, direct photography of the flame using a color high-speed video camera and magnified shadow imaging of spray droplets using a monochrome high-speed video camera were used. The frequencies of secondary atomization are also discussed.

2. Experiment
2.1 Preparation of the emulsified fuel

Sorbitan monooleate (Emasol O-10V, Kao Corp. HLB = 4.3) was used as the emulsifying agent to prepare a water-in-oil (W/O) emulsified fuel. The water content of the emulsified fuel was 10 vol% and the amount of surfactant added to the emulsified fuel was 0.75 vol.%. A 250 ml volume of W/O emulsified fuel was prepared by adding water and emulsifying agent to n-dodecane and stirring the mixture for 20 min with a mechanical homogenizer (Omni Homogenizer, GLT-115, Yamato Science Co., Ltd, Japan) at a rotational speed of 9,000 rpm.

An ultrasonic atomizer was used in the burner. The size distribution of the dispersed water droplets in the emulsified fuel was measured after atomization, because the size of the dispersed water droplets could potentially change during the atomization process. WinRoof Ver 5.01 (Mitani Corp.) software was used to analyze the droplet sizes from the photographs. Dispersed droplets smaller than 1.0 µm were not measured due to experimental uncertainties.

2.2 Magnified shadow imaging technique for spray flow

Figure 1 shows a schematic diagram of the experimental apparatus used for visualizing droplet behavior in a flame. The experimental apparatus can be divided into a shadow imaging system (described here) and a counterflow burner (described in Section 2.3). A high-speed video camera and a metal halide lamp (LS-M350, Sumita co. Ltd) as a light source, were positioned opposite to each other to examine shadows of the droplets. A monochrome high-speed video camera (Phantom V12.1, Vision Research) with a zoom microscope and with a maximum zoom ratio of 12 (DZ4, Union optical co. Ltd.) was used to record the shadows of the spray droplets. The image resolution was set to 128×128 with a frame rate of 180,064 fps and an exposure time of 4.82 µs. The spatial resolution was 12.0 µm/pixel. In addition to this shadow imaging, a color high-speed video camera (Phantom V12.1, Vision Research) and lens (Nikkor 50 mm F1.2, Nikon) were used for direct photography of the flame. The light source was not used for direct color photography.
and the image resolution was $256 \times 256$ with a frame rate of 7,000 fps and an exposure time of 100 $\mu$s. The spatial resolution was 20.0 $\mu$m/pixel. In both the observations, the high-speed video camera was mounted on a three-dimensional (3D) traverse system, which allowed the camera to move in three directions.

![Schematic diagram of experimental setup for visualizing droplets in spray flame](image)

**Fig. 1** Schematic diagram of experimental setup for visualizing droplets in spray flame

### 2.3 Counterflow burner

Figure 2 shows a photograph and schematic diagram of the laminar counterflow burner. The upper and lower ports are coaxially mounted opposite to one another. The details of the laminar counterflow burner are described elsewhere (Watanabe, et al., 2007; Hayashi, et al., 2011; Hayashi, et al., 2013). An ultrasonic atomizer operating at 18 kHz was used to feed liquid fuel to the burner from a tank pressurized by $N_2$. The atomizer was attached at the top of the upper burner port. The carrier gas (air) entered from the upper burner port below the atomizer. Two phase flow of air and fuel spray were issued to the counterflow field from the upper burner port. $CH_4/air$ premixed gas (equivalence ratio $\phi_g = 0.6$) flowed into the counterflow field from the lower burner port.

Figure 3 shows a schematic diagram of the stabilized flames in the laminar counterflow field. The stagnation plane, a gaseous flame from the lower burner port, the spray flame region, and the gas streamline are shown in the diagram. Droplet behaviors at each of the three measuring points located along the centerline were visualized by the magnified shadow imaging system, as described in Section 2.2.

![Laminar counter flow burner](image)

**Fig. 2** Laminar counter flow burner

![Schematic diagram of flame and measuring points](image)

**Fig. 3** Schematic diagram of flame and measuring points
Experimental conditions are listed in Table 1. The fuel flow rate of n-dodecane was set to be equivalent to that of the emulsified fuel. For detailed study of secondary atomization, it is needed to visualize droplets individually. Therefore, lean spray conditions ($\phi = 0.032$ and 0.028) were used in this study. Gaseous flame ($\text{CH}_4$) was used to stabilize lean spray flame. Spray droplets penetrating into flame were simulated by gaseous flame. Experimental equipments and conditions were suited to visualize droplet behavior during secondary atomization in the spray flame.

### Table 1 Experimental conditions

<table>
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<tr>
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<th>Liquid fuel</th>
<th>n-dodecane ($\text{C}<em>{12}\text{H}</em>{26}$)</th>
<th>emulsified fuel</th>
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<td>Liquid fuel flow rate [g/min]</td>
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<td>0.177</td>
<td></td>
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<tr>
<td>Liquid fuel equivalence ratio ($\phi_{\text{liquid}}$) [-]</td>
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<table>
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<th>$\text{CH}_4$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.6</td>
</tr>
<tr>
<td>Gas velocity ($v_{\text{gas}}$) [m/s]</td>
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<td>0.91</td>
</tr>
<tr>
<td>Strain rate [1/s]</td>
<td>60.4</td>
<td>60.4</td>
</tr>
</tbody>
</table>

3. Results and discussion
3.1 Preparation of the emulsified fuel

Figure 4 shows the size distribution of the dispersed water droplets in the emulsified fuel after spray injection. The number mean diameter ($d_{\text{w,ave}}$) is 5.1 $\mu$m. In our previous study, the number mean diameter of the dispersed water in an emulsified fuel after atomization was 2.9 $\mu$m, even though the emulsified fuel was prepared using similar methods (Watanabe and Okazaki, 2013). The difference in atomizers used in these studies might have caused the difference in the droplet sizes of the dispersed water. Moreover, in this study, a larger volume of emulsified fuel was prepared for the spray flame, resulting in a larger size of dispersed water droplets.

![Fig. 4 Size distribution of the dispersed water droplets](image)

3.2 Photographs of secondary atomization in emulsified fuel spray

Figure 5 shows a series of direct photographs of the flame of n-dodecane (a) and emulsified fuel (b). During the measurement, individual droplet flames were infrequently observed at $z = 0$-8 mm. The flames observed in this study mainly consisted of droplet flames and luminous flames. In the flame of n-dodecane, individual blue flames (droplet flames) were observed in the upstream region. In the flame of emulsified fuel, “bright spots,” which were of similar or
higher luminosity than the surrounding area, were observed scattered around the luminous flame. The droplet flame appeared to be rapidly expanding because of secondary atomization. However, the frequency of occurrence of bright spots was nearly negligible in the flame of n-dodecane. Previous studies reported “glowing spots” or “bright spots” in the burning flame of the emulsified fuel (Ochoterena, et al., 2010; Huo, et al., 2014). As previously mentioned, secondary atomization is an acceptable explanation for these bright spots. However, the droplet behaviors in the spray flame are still unclear by direct photography. Meanwhile, luminous flame area of emulsified fuel was larger than that of n-dodecane in Fig. 5. Although soot was likely to form in emulsified fuel, there are two possible reasons for the difference. First, high-speed images (7,000 fps) that well capture individual droplets were used in Fig. 5. It was difficult to compare these flame images from the viewpoint of combustion characteristics because instantaneous fuel flow rate of emulsified fuel might differ from that of n-dodecane fuel during the short period of 0.001 s. And, local equivalence ratio was not uniform in spray flame. Another possible reason was characteristics of lean spray flame stabilized by gaseous flame. This will be discussed later.

Fig. 5 Series of direct photographs of the flame
Figure 6 shows instantaneous photographs of droplet shadows of emulsified fuel at $z = 3$ mm (a), 6 mm (b), and 9 mm (c) along the center line. The number of droplets was observed to decrease in the downstream direction because of evaporation. As shown in Figs. 6(b) and (c), droplets were clearly visualized even in the luminous flame that formed around $z = 5$-15 mm. “Glowing spots” or “bright spots” are often used as evidence of secondary atomization; however, these spots were hardly observed in the luminous flame because the brightness caused by secondary atomization was overtaken by the brightness of the luminous flame. However, the shadow imaging technique provides droplet behavior regardless of the flame emission.

Fig. 6 Instantaneous photographs of droplet shadows (128 x 128) on the centerline (emulsified fuel)

Figures 7 and 8 show a series of photographs of secondary atomization in the emulsified fuel spray flame at $z = 6$ mm on the centerline. From previous studies, secondary atomization can be classified into micro-explosion, partial micro-explosion, and puffing (Fu, et al., 2002; Watanabe, et al., 2009; Watanabe and Okazaki, 2013; Huo, et. al., 2014). Partial micro-explosion occurs when a large part of the droplet bursts in comparison with the bursting of the entire droplet in complete micro-explosion. Puffing and partial micro-explosion are observed in Fig. 7, and micro-explosion is observed in Fig. 8.

Fig. 7 Series of photographs of puffing and partial micro-explosion in emulsified fuel flame ($z = 6$ mm, centerline)

Fig. 8 The series of photographs of micro-explosion in emulsified fuel flame ($z = 6$ mm, centerline)
Our previous study showed that complete micro-explosion was rarely observed in emulsified fuel spray flow; however, puffing and partial micro-explosion were observed (Watanabe, et al., 2013). The main differences between the present and previous studies are the temperature and size of the dispersed water droplets. In our previous study, the emulsified fuel spray having an average dispersed water droplet size of 2.9 μm was heated under N\textsubscript{2} in a furnace with a wall temperature of 823 K. In contrast, the emulsified fuel droplets are heated in the flame and the average size of the dispersed water droplets is 5.1 μm in the present study. The effect of size of the dispersed water droplets on secondary atomization has been discussed by some researchers (Yoshimoto, et al., 1989; Fu, et al., 2002; Takeda, et al., 2008; Suzuki, et al., 2011; Mura, et al., 2012; Watanabe and Okazaki, 2013). Yoshimoto et al. (1989) and Fu et al. (2002) showed that micro-explosion strength increased with increasing dispersed droplet size. Suzuki et al. (2011) also showed that the occurrence probability of micro-explosion increased with an increase in the dispersed water droplet diameter. Moreover, it was previously demonstrated that large dispersed water droplets improved the intensity of secondary atomization and provided a finer spray flow (Watanabe and Okazaki, 2013). Considering above previous studies, the large dispersed water droplets used in the present study might be the reason why complete micro-explosion was observed in the present experiments. Meanwhile, the effect of size of the dispersed water droplets on secondary atomization is complicated. In addition to above factors, it was reported that the dispersed water size also influenced droplet temperature at micro-explosion (Mura, et al., 2012). More detailed work is necessary to study the effect of dispersed water size and gas temperature on secondary atomization.

Figure 9 shows a series of photographs of a spray droplet moving randomly due to vapor blowout. After the sequences of puffing (Puffing 1-3), micro-explosion occurred at 23/180,064 s. On the centerline, spray droplets vertically fell in the counterflow burner; however, the emulsified fuel droplets randomly moved when secondary atomization occurred. Just before Puffing 3, vapor is observed to form inside the droplet at 9/180,064 s. Subsequently, vapor blows out from the droplet surface toward the right. After the blowout, the droplet moves in the direction opposite to the blowout (the left). During the period from 10/180,064 s (Puffing 3) to 22/180,064 s (just before micro-explosion), the droplet moves about 150 μm. On the centerline, the gas velocity along the transverse direction was negligible. If droplet motion in the depth direction is assumed to be negligible, the increase in droplet velocity because of the vapor blowout can be determined to be about 2.3 m/s. In fact, vapor blowout in secondary atomization is observed to accelerate droplet velocity, and leads to random movement of the spray droplet. An increase in the droplet velocity by secondary atomization was often observed through measurements. It was difficult to measure the exact droplet velocity after puffing because the depth direction could not be measured in this experiment. The puffing, partial micro-explosion, and micro-explosion shown in Fig. 7 and Fig. 8, and the random movement of the droplet shown in Fig. 9 are expected to cause “bright spots” as shown in Fig. 5 (b) because of rapid evaporation and spread of fuel vapor.

3.3 Photographs of secondary atomization in emulsified fuel spray

To discuss the frequencies of secondary atomization, the number of droplets in which secondary atomization occurs were counted by the observations of series of photographs. The spray droplet sizes just before secondary atomization were also measured. Because some partial micro-explosions were very close to complete micro-explosion, it was difficult to separate partial micro-explosion from micro-explosion. Therefore, in this section, micro-explosion includes both partial and complete micro-explosions. The number of frames used for the observation was 12,000 frames at z = 3 mm and 20,000 frames at z = 6 and 9 mm, respectively.

Figure 10 shows the frequencies of micro-explosion, puffing, and the spray size at z = 3 mm and 6 mm. The frequencies of puffing or micro-explosion are given as the number of puffing or micro-explosion counted normalized by the total number of droplets at each axial location. The observed total number of droplets was 385, 51, and 14 at z = 3, 6, and 9 mm, respectively. Since evaporation is progressed at the downstream, the droplet is less observed at z = 6 mm than at z = 3 mm; however, the significant difference in secondary atomization frequency between z = 3 mm and 6 mm is seen. At z = 3 mm, the frequencies of puffing and micro-explosion were significantly low, and were only observed in small droplets (< 50 μm). However, at z = 6 mm where the luminous flame was formed, the frequencies of puffing and micro-explosion significantly increased, and puffing was dominant compared with micro-explosion. Interestingly, puffing and micro-explosion were observed in various sizes of droplets less than 70 μm at z = 6 mm, in contrast to those at z = 3 mm. The total number of droplets was significantly diminished at z = 9 mm because evaporation was rapidly progressed between z = 6 and 9 mm in the luminous flame. Evaporation was almost completed at z = 9 mm. It was difficult to define the frequencies of puffing and micro-explosion at z = 9 mm because the number
of droplets was insufficient. Although only a few droplets appeared, puffing and micro-explosion were observed in larger droplets of around 80 \( \mu \text{m} \), and frequency of micro-explosion increased at \( z = 9 \text{ mm} \). In fact, the maximum size of droplets for which secondary atomization occurred increased in the downstream region where the luminous flame was formed. These results suggest that larger droplets require greater heat to exhibit secondary atomization. Besides their heat capacity, the size of the spray droplet might influence other factors, such as the coalescence of the dispersed water in the inner droplet, which are related with secondary atomization (Segawa, et al., 2000; Watanabe, et al., 2010; Suzuki, et al., 2011; Mura, et al., 2014; Califano, et al., 2014).

When emulsified fuel was used in actual spray combustion, the gas temperature was reduced in the upstream region due to water existence; however, gas temperature increased rapidly in downstream region due to secondary atomization, and combustion characteristics were improved (Watanabe, et al., 2008). In this study, secondary atomization seemed to improve droplet evaporation due to dramatic change in droplet size and random movement as shown in Figs. 7-9. However, lean spray flame was stabilized by gaseous flame located downstream in this study. Gaseous flame strongly enhanced droplet evaporation. With increasing droplet evaporation rate, the effect of secondary atomization on combustion characteristics becomes relatively less important. This was another reason for larger luminous flame area of emulsified fuel in Fig. 5. Although secondary atomization could reduce the soot formation, it was difficult to discuss the effect of secondary atomization on macro flame characteristics in this study.

![Fig. 9 The series of photographs of droplet behavior in the flame (z = 6mm, centerline)](image-url)
4. Conclusions

In this study, secondary atomization characteristics of emulsified fuel were studied in the flame stabilized in a laminar counterflow field. Direct photography of the flame using a color high-speed video camera and magnified shadow imaging of spray droplets using a monochrome high-speed video camera were used, and the relationships between the flame characteristics and droplet behaviors of the emulsified fuel were discussed. As a result, the direct photography of the flame showed “bright spots” around the luminous flame when emulsified fuel was used. This was linked to droplet behaviors such as puffing, partial micro-explosion, and micro-explosion visualized by magnified shadow imaging. In addition, vapor blowout in secondary atomization was found to accelerate droplet velocity, and lead to random motion of the spray droplet. It was suggested that secondary atomization caused rapid evaporation and spread of fuel vapor. The magnified shadow imaging technique provided a clear description of the droplet behavior in the flame, and numerous puffing and micro-explosion were observed regardless of the flame emissions. It was shown that the frequency of secondary atomization increased in the downstream region where the luminous flame was formed. Secondary atomization occurred in droplets with various sizes in the downstream region, whereas it occurred in only small droplets at the upstream region where the luminous flame was not formed.

References


