Development of Partially-Premixed Spray Burner and Observation of Flame Structure

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Mono-sized and monodispersed fuel spray (homogeneous spray) flames were studied as a simple model of partially-premixed spray flames to understand the effect of a large number of fine fuel droplets on flame propagation and flame structure. Homogeneous spray burner was newly developed in this work and performance tests were done. Laminar spray stream was generated successfully at normal and microgravity. The mean droplet diameter was controlled by changing pressure reduction time. A secondary flame was observed for homogeneous spray flames both on fuel lean side and on fuel rich side.

1. Introduction

Spray combustion is employed to various combustors such as a diesel engine, a gas turbine and an industrial furnace. Understanding spray combustion mechanism improves the efficiency of combustors and reduces exhaust gases causing environmental pollutions. Since the combustion mechanism of spray is complicated, very little is known about the details. Many approaches to understand the spray combustion mechanism have been carried out [1-6]. Especially, investigations of single droplet combustion, droplet array combustion and droplet matrix combustion have been reported in literatures for long time [7, 8]. However, there is a theoretical gap between understanding about droplet combustion and real spray combustion. For example, the number of droplets is quite different. Studies on homogeneous spray combustion are important to relate the knowledge of droplet combustion to real spray combustion.

Hayashi and Kumagai [9] generated homogeneous fuel sprays using the principle of the Wilson's cloud chamber. They set the ignition pressure below 0.1 MPa, and the mean droplet diameter was set at about 7 μm. They investigated the effects of fuel droplets suspended in premixtures on flame shape, flame speed, burning time, and maximum burning pressure. The effects of fuel droplets on the burning characteristics are more significant for fast burning mixtures than slow burning mixtures, suggesting that ethanol droplets of several microns in diameter are not completely evaporated in the preheating zone.

The basic study of homogeneous spray combustion with a constant pressure chamber and a constant volume chamber has been investigated in the previous work [10, 11]. The results show that fine fuel droplets suspended in a premixture affect flame propagation speed and maximum burning pressure. It is important to clarify the interaction between fuel droplets and a propagating flame. Homogeneous spray burner was newly developed in this work and performance tests were done. Condensation method using rapid pressure reduction of saturated fuel vapor-air mixtures was employed to generate homogeneous fuel spray. Advantages of this spray generation method are that droplet diameter distribution is narrow and that velocity difference between gas phase and droplets can be minimized. Standing homogeneous spray flames were used for the observation of flame structure because they are more suitable for detailed observation than spherical progress flames. Gas equivalence ratio is possible to be controlled by changing of the spray stream temperature. Laminar homogeneous spray flow was made with a coaxial burner. Microgravity experiments using the homogeneous spray burner were performed for large droplet sprays since large droplets fall down during spray generation process by gravity.

2. Experimental apparatus and procedure

Homogeneous spray was generated by the condensation method using rapid pressure reduction of saturated fuel vapor-air mixtures. The principle of this method is the same as that of the Wilson's cloud chamber. Ethanol and air were used as a fuel and an ambient gas, respectively.

2.1. Experimental apparatus

To make a uniform flow velocity distribution in a spray, a coaxial flow nozzle burner was employed. Figure 1 shows experimental apparatus consisting of the homogeneous spray burner, the measuring device and the controller.

Figure 2 outlines the homogeneous spray burner. The spray burner consists of a rapid expansion chamber, a piston, a nozzle, a lid and a flange. Spray was generated in the rapid expansion chamber. The nozzle exit is 8 mm in diameter and is jacketed by a stream of N_2. A rectifier was installed within the N_2 stream. The inner diameter of rapid expansion chamber is 80 mm. Temperature drop of the mixture causes temperature difference between the mixture and the rapid expansion chamber wall. This temperature difference causes natural convention and heat flux from the wall to the mixture. To suppress natural convection and the heat flux, the burner has double wall structure and flon 134a is injected into the space between inner and outer walls during the rapid pressure reduction. The piston pushed out the homogeneous spray after rapid pressure reduction of a saturated fuel vapor-air mixture. The flow velocity at the nozzle exit can be varied up to 0.9 m/s. A lid to seal up the nozzle exit and an ignition wire are mounted on the swing arm. The homogeneous spray burner is equipped with electric heaters to control temperature of fuel vapor-air mixtures prepared in the rapid expansion chamber. A resistance thermometer to measure the mixture temperature and an R type thermocouple to measure a temperature drop during rapid expansion are located at the top-center of the rapid expansion chamber.

The mean droplet diameter was measured with a LDSA (Laser Droplet Size Analyzer) which calculates droplet diameter from Fraunfofer diffraction. Fuel sprays were observed using laser sheet method, in which the copper vapor laser (wavelength 511 nm, pulse width 20 – 30 ns) was used as a light source, and the spray image was recorded using a high-speed video camera. Laser light illuminated the perpendicular section including a burner center axis 10 mm above the nozzle exit. The copper vapor laser and the high-speed video camera were synchronized at 1 kHz. Standing flames at the exit of the burner were observed by the direct photograph method with a color CCD camera.

For microgravity experiments using an aircraft, a saturated fuel vapor-air mixture feeder and a hood were added to the experimental apparatus. The fuel vapor-air mixture feeder is employed to shorten the interval of experiments. The hood covers the nozzle exit to maintain pressure at 0.101 MPa, and to exhaust combustible gas and burned gas out of the aircraft.

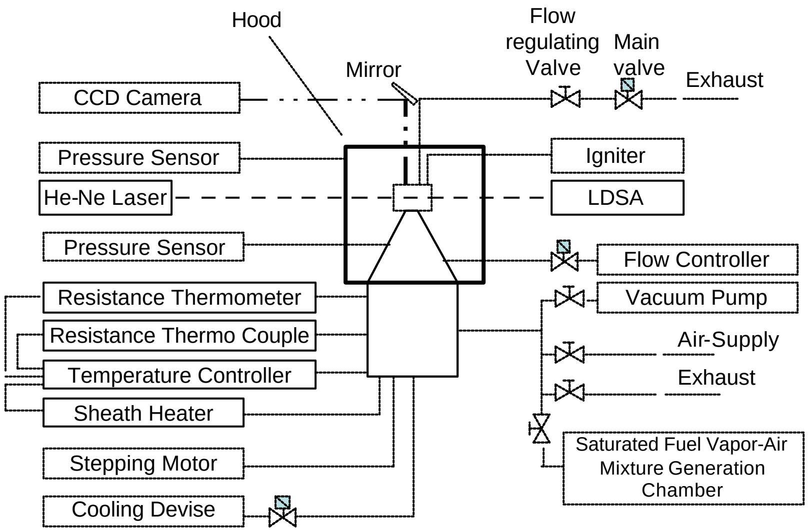


Fig. 1 Experimental apparatus.

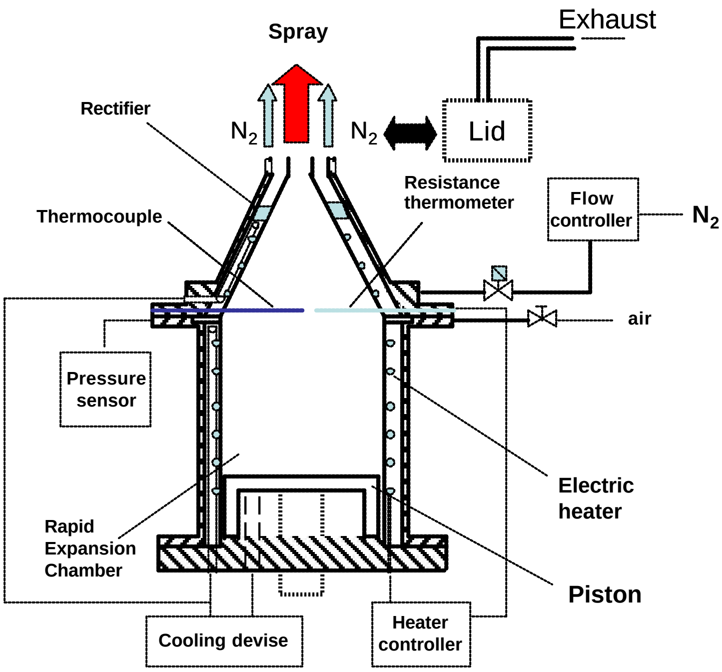


Fig. 2 Homogeneous spray burner.

2.2. Procedures

Ethanol is injected into the rapid expansion chamber with a syringe and air is fed from a high-pressure cylinder. The rapid expansion chamber was heated up to an initial temperature and kept at 30 minutes. In case of microgravity experiments, saturated fuel vapor-air mixture supplied by the saturated fuel vapor-air mixture feeder is led to the rapid expansion chamber after the rapid expansion chamber was heated up to an initial temperature. Homogeneous spray is generated by opening a main valve. After rapid pressure reduction, the lid is move away by the swing arm. At the same time, measurement of mean droplet diameter is started. In microgravity experiments, the main valve is opened after microgravity environment was achieved. The generated homogeneous spray is pushed out of the nozzle exit by the piston at a constant flow velocity. Ignition wire is introduced into spray stream, and the spray is ignited. The ignition wire is moved away from the spray stream after ignition is confirmed. The image taken by CCD camera is recorded with a digital tape reorder.

3. Result and discussion

Saturated fuel vapor-air mixtures were used as an initial mixture for all experiments. Therefore, total equivalence ratio ϕ_t can be determined from the temperature and pressure of the mixture before the rapid pressure reduction. Gas equivalence ratio ϕ_g was obtained from the gas phase temperature and pressure just before the ignition wire was heated up. Liquid equivalence ratio ϕ_l was defined as (ϕ_t - ϕ_g).

3.1. Homogeneous spray generation at normal gravity

Figure 3 and 4 show temporal variations of Sauter mean droplet diameter d_m and volume concentration at normal gravity. The pressure reduction times t_R were 0.8 and 3.5 s, respectively. The origin of time axis is the time when the piston started to push out homogeneous spray. Open triangles indicate the value proportional to the volume concentration of droplets and closed circles indicate mean droplet diameter. In Fig. 3, the mean droplet diameter of the homogeneous spray pushed out of the burner exit is steady at 5 μm. Due to longer pressure reduction time, the mean droplet diameter in figure 4 is larger than the case of Fig. 3. The temporal variation of the mean droplet diameter is unsteady. It is supposed that downward flow caused by sedimentation of large droplets induces the unsteadiness of the spray steam. Concentration of the mean droplet diameter was unsteady regardless of the mean droplet diameter. Figure 5 and 6 show typical mean droplet diameter distributions 5 s after rapid pressure reduction under normal gravity conditions. The mean droplet diameters are 5 and 20 μm, respectively. The width of distribution is narrower for d_m = 20 μm than d_m = 5 μm. Large droplets fell down by gravity while the main stream pushed out the droplets from the nozzle exit. In case of the spray with large mean droplet diameter, it is understood that the droplets did not come out from the nozzle exit because sedimentation velocity of the large droplets contained in homogeneous spray exceeded the main stream velocity.

Figure 7 shows a spray stream observed by laser sheet method. Width and brightness of the spray stream are almost constant in the range of spray stream illuminated by laser sheet. It was confirmed that a spatially-uniform stream is generated.

3.2. Homogeneous spray generation at microgravity

Figure 8 shows temporal variation of mean droplet diameter and volume concentration at microgravity. The pressure reduction time was 3.7 s. The mean droplet diameter is steady at 6 μm. Compared with Fig. 3, the mean droplet diameter and the concentration at microgravity are steadier than at normal gravity. The mean droplet diameter ranges from 2 to 6 μm for microgravity experiments and from 4.5 to 25 μm for normal gravity experiments. The reason why sprays of large mean droplet diameter were not generated at microgravity is supposed to be due to using the saturated fuel vapor-air mixture feeder, which is not used for normal gravity experiments. Since the temperature of the feeder is higher than the rapid expansion chamber, a portion of fuel vapor condenses onto small droplets when vapor is fed to the rapid expansion chamber. The reason why the mean droplet diameter of sprays did not vary though the pressure reduction time was changed is supposed to be that these droplets remained until rapid pressure reduction and fuel vapor condensed onto these droplets during rapid pressure reduction.

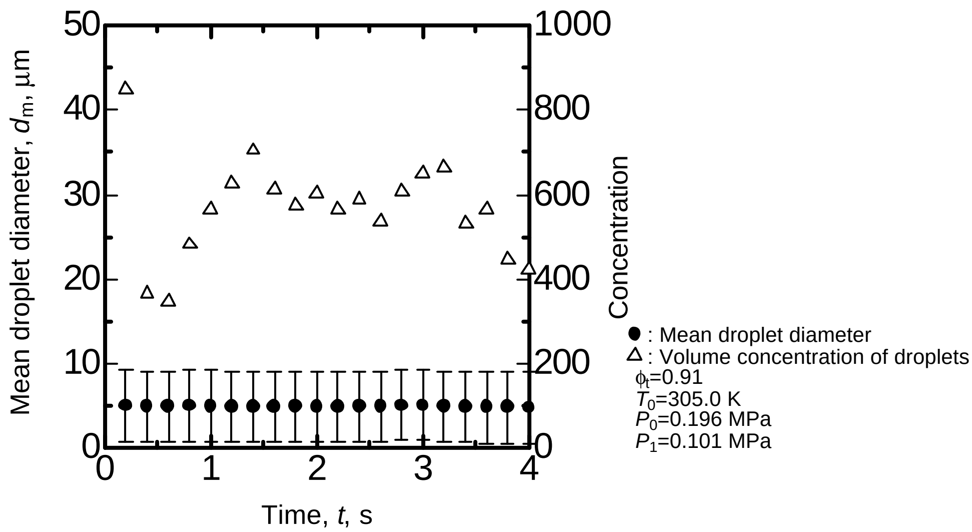


Fig. 3 Temporal variations of the mean droplet diameter and volume concentration at normal gravity in case of short pressure reduction time.

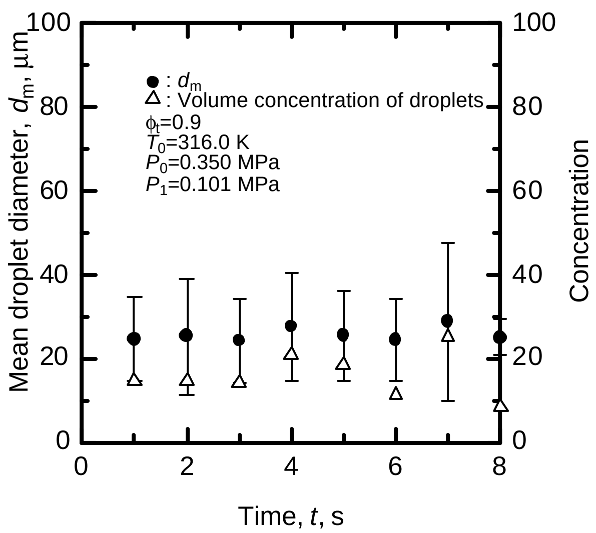


Fig. 4 Temporal variations of the mean droplet diameter and volume concentration at normal gravity in case of long pressure reduction time.

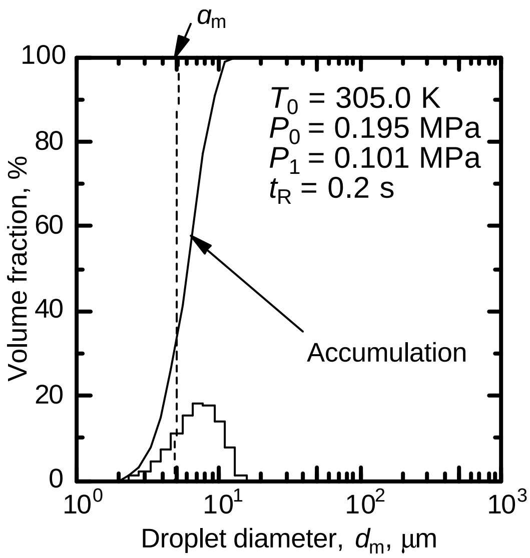


Fig. 5 Typical droplet diameter distribution for small droplet spray stream at normal gravity. (d_m = 5 μm)

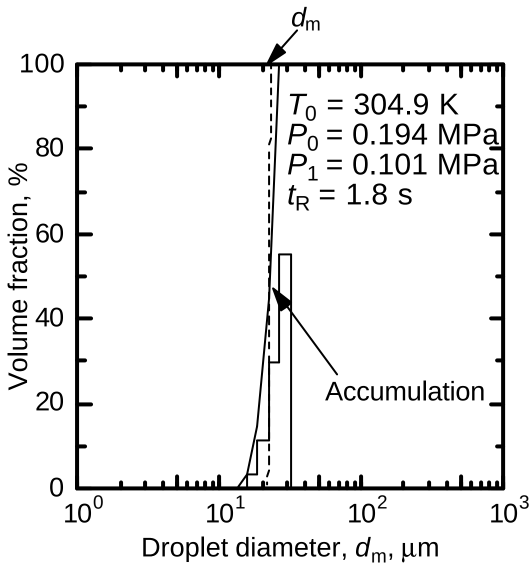


Fig. 6 Typical droplet diameter distribution for large droplet spray stream at normal gravity. (d_m = 20 μm)

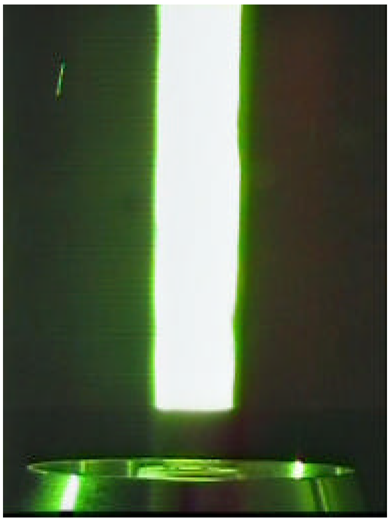


Fig. 7 Spray stream observed by laser sheet method.

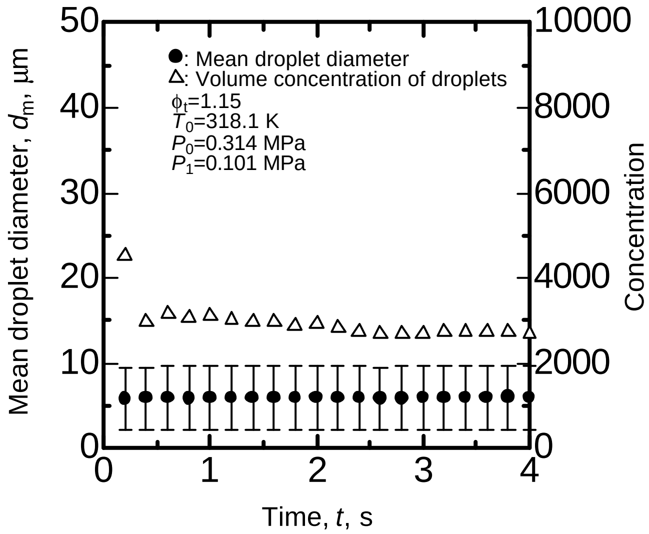


Fig. 8 Temporal variations of the mean droplet diameter and volume concentration at microgravity.

3.3. Observation of flames

Figure 9 and 10 show direct photographs of flames with total equivalence ratios 0.9 and 1.2, respectively. Liquid equivalence ratios were set at 0.35 and the mean droplet diameters were 5 and 20 μm for homogeneous spray flame. Photographs of a premixed flame with the same total equivalence ratio are shown in the figures to compare flame structures. The homogeneous spray flames had a secondary flame for all cases. It is supposed that, since fuel droplets did not evaporate completely in the preheating and reaction zones, the fuel droplets evaporated and burned after going out of the reaction zone. The primary flame was blue and the secondary flame was purple-blue. Light emission from the secondary flames of d_m = 20 μm was stronger than that of d_m = 5 μm. The reason was supposed to be that large fuel droplets remained after going out of the primary flame in case of d_m = 20 μm. The flame of the spray of ϕ_t = 0.9 and d_m = 20 μm had a column shape. The velocity of spray stream was extremely large for a column flame. The effect of large fuel droplets on flame structure is necessary to be studied in detail.

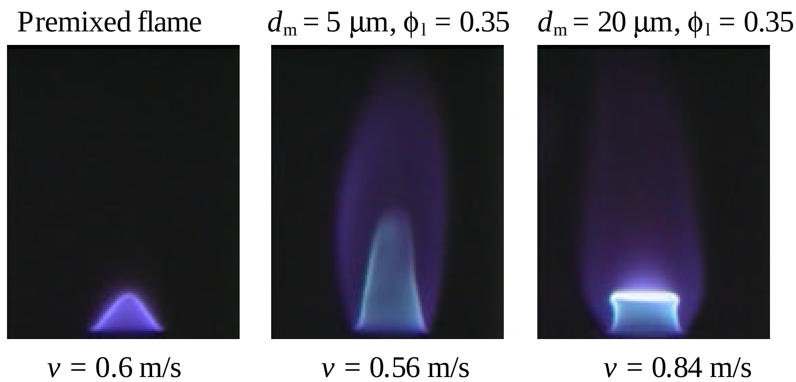
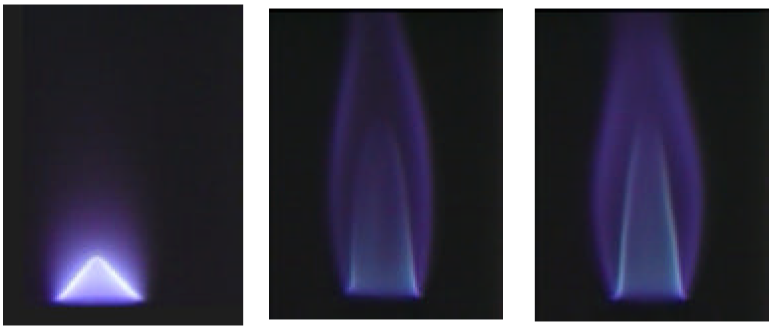


Fig. 9 Direct photographs of flames. (ϕ_t = 0.9)

Premixed flame d_m = 5 μm, ϕ_l = 0.35 d_m = 20 μm, ϕ_l = 0.35



v = 0.76 m/s v = 0.53 m/s v = 0.67 m/s

Fig.10 Direct photographs of flames. (ϕ_t = 1.2)

4. Conclusion

A homogeneous spray burner was developed to observe details of the flame structure. Partially-premixed spray streams were generated successfully using a newly developed homogenous spray burner. Spray streams were able to be generated uniformly for a several seconds. The spray generated at microgravity is steadier than at normal gravity.
Combustion experiments were performed at normal gravity. The difference of the structure was found between the premixed flame and the homogeneous spray flame. A secondary flame was observed for the homogeneous spray flames both on fuel-lean side and on fuel-rich side.

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