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航空機の放物線飛行を利用したアルミニウム粉塵爆発実験
Microgravity experiments of aluminum dust explosion on parabolic flight

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1. Introduction

Dust mitigation is one of critical technology developments for human exploration of Mars, because powder handling process in a reduced-gravity environment have difficulties unlike a normal gravity environment, dispersed particle continues suspending without gravitational sedimentation [1-4]. However, dust explosion in microgravity environments has not been considered in detail despite necessity for sustained human space exploration, lunar resource extraction and utilization. All parameters included in a risk assessment of dust explosions depend on flame propagation behavior through dust dispersion. To prevent and mitigate dust explosion accidents, the flame propagation mechanism through dust explosion requires to be elucidated by the quantitative measurement of flame-particle interaction [5]. Moreover, fundamental research on the combustion of solid particle has the difficulties in ground-based experiments such as a flow induced by particle dispersion and particle settling. The aim of this study is to investigate the effect of aluminum particle dispersibility on the flame propagation. Another objective is to develop an overarching framework the microgravity experimental apparatus including the simultaneous observation system and to demonstrate the feasibility of long-term microgravity test.

2. Experiments

2.1 Experimental setup

The microgravity experimental apparatus was developed based on safety requirements of parabolic flights aboard MU300 aircraft operated by Diamond Air Service. Inc. (DAS). Experimental systems were loaded on MU300 experimental shelf of W600 mm×D450 mm×H900 mm (**Fig. 1**). The core of the experimental setup arrangement was the observation tube made of acrylic (inner, W30 mm×D30 mm×H250 mm, 0.225 L), and spare tubes were loaded next to the experimental shelf to change in each experiment. Top of the tube was semi-open-end structure consisted of stainless mesh and the connection with exhaust chamber, which confined combustible particles in the tube but also prevented the pressure rise caused in every combustion experiment. This structure assumed that flame propagates only inside the observation tube. The observation tube was enclosed by aluminum combustion chamber with three quartz windows that satisfied the regulation of a combustion experiment on the aircraft. In the beginning of each microgravity experiment, aluminum powder with median diameter of 22 μm (Toyo Aluminium K.K.) was dispersed into the tube by air flow discharging of 120 kPa compressed air for 2 seconds. 8 seconds after the end of particle dispersion, aluminum dust was ignited by electric discharge of 15 kV. The simultaneous observation system surrounded combustion chamber and started to record 2 seconds before the ignition timing. Two high-speed cameras FASTCAM AX100 (Photron) observed aluminum dust illuminated by laser sheet and flame propagation simultaneously at 3000 frames per second.

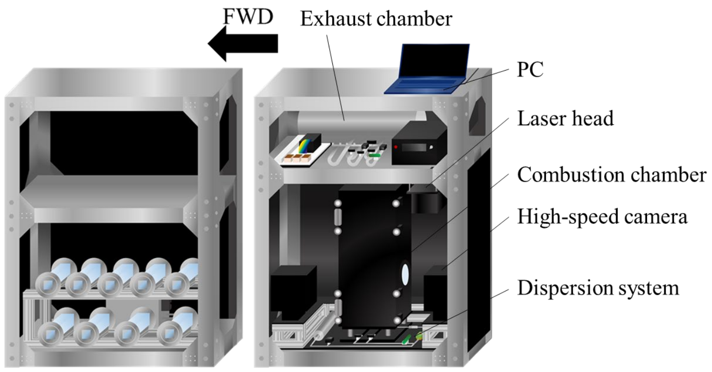

Figure 1. The microgravity experimental apparatus for dust explosion using a parabolic flight.

2.2 Results and discussion

To evaluate aluminum particle velocity that affects a combustion experiment, particle imaging velocimetry (PIV) were conducted from the high-speed images of particles illuminated by 1 mm thickness of laser light sheet. **Figure. 2** shows flow fields of aluminum particle before ignition timing in a parabolic flight experiment. The x-y plane is in the middle of the observation tube and y is parallel to vertical axis on the aircraft. Measured mean particle velocity (calculated by $\sqrt{u_x^2 + u_y^2}$) is slower than 3.9 cm/s, terminal velocity of 22 μm aluminum particle estimated by Stokes' law. The results demonstrated the effect of dispersion flow on the particle behavior is decreased during 8 seconds of ignition time delay, and the vectors in a flow field indicate that dispersed particles keep suspending in a reduced-gravity environment. Although the particle velocity became slower, distribution of particle velocity seems to be ununiform, vary from several mm/s to 1 cm/s. The reason is there are the effects of g-jitter in all directions during a parabolic flight experiment using an aircraft. The distribution of dust concentration before ignition timing is shown in **Fig. 3**. Aluminum dust continued to be suspended in air, and dust concentration indicated a minor change during ignition time delay. Despite the enough time for aluminum particle to settle out in a gravitational field, the risk of dust explosion lasts in a microgravity environment because the particle sedimentation does not occur. The distribution of dust concentration demonstrated heterogeneous field and kept its location during the observation.

After ignition time delay, aluminum dust was ignited and then flame propagation was observed. Flame propagation speed on the coordinates of the observation tube decreased with decreasing duct concentration. In addition to the effect of g-jitter on particle dispersibility, g-jitter affects the flame propagation behavior by natural convection therefore the quality of gravity during a microgravity experiment is one of the negligible parameters. Future studies could fruitfully explore this issue further by the ideal experimental environments such as a sounding rocket and the International Space Station (ISS).

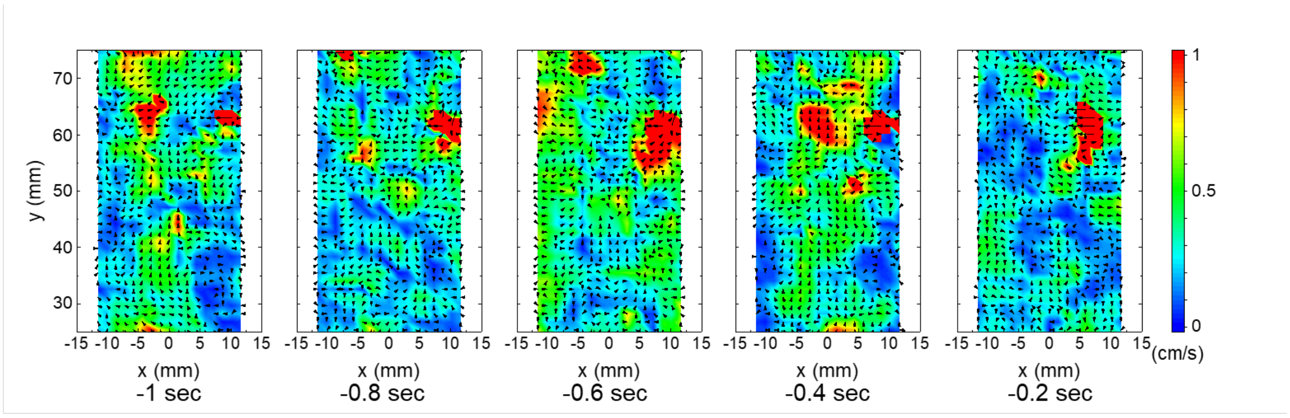

Figure 2. Particle speed distribution before ignition timing (y is distance from ignition point).

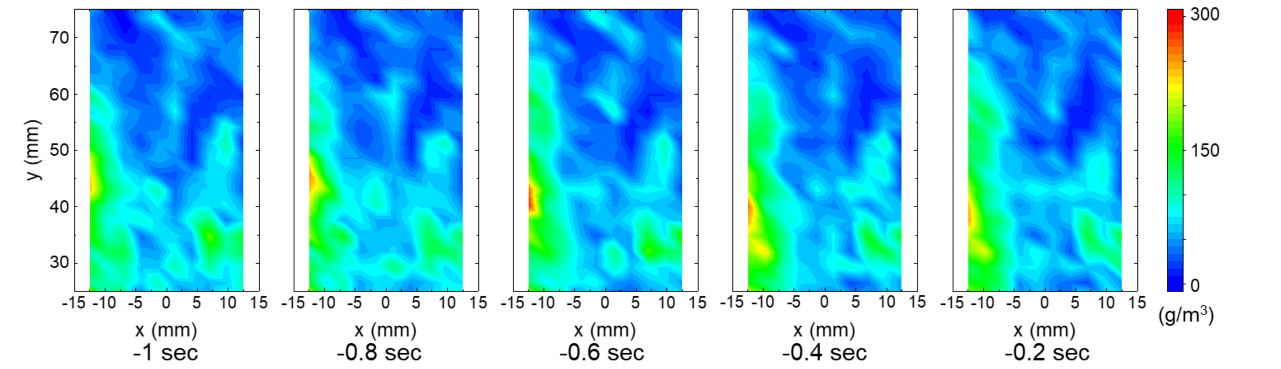

Figure 3. Dust concentration before ignition timing (y is distance from ignition point).

3. Conclusions

The microgravity experiments using parabolic flight on aircraft MU300 were conducted to evaluate the effect of particle dispersibility on flame propagation behavior. Ignition time delay after the end of particle dispersion decreased gas flow generated in particle dispersion, this accounts for long-duration microgravity experiment enable to conduct a dust explosion experiment in a quiescent gas condition. However, each microgravity experiment using a parabolic flight has g-jitter which affects combustion phenomena in natural convection. Future studies could overcome this issue to investigate flame propagation mechanism of aluminum dust explosion by microgravity experiments such as sounding rockets.

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