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Group Combustion-2，－液滴群燃え広がりにおける冷炎発生調査－，準備状況報告

Current State of Group Combustion-2, - Investigation of Cool-flame during Flame Spread over Droplet Clouds -

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1. Background and Purpose

The stable combustion of liquid fuels such as in aero engines requires the flame to spread to the fuel spray near the flame base and group-combustion excitation. In order to control the flame spread in the spray without relying on trial-and-error for high-efficiency combustion, we need to understand the flame-spread mechanism and develop models and simulation methods that well describe group-combustion excitation through flame spread.

We proposed a new percolation model that employs flame spread between droplets as the local connection rule and describes flame spread over a randomly distributed droplet cloud as a complex system and studied the group-combustion-excitation mechanism [1)].

We conducted droplet-cloud combustion experiments titled "Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds (Group Combustion)" in 2017 as the first combustion experiments aboard the Japanese Experiment Module, Kibo, on ISS [2-10)]. The local flame-spread rule was studied in detail using large-scale droplet clouds, droplet-cloud elements, droplet-cluster arrays and movable droplets generated in the Group Combustion Experiment Module (GCEM). Except for the experiments with movable droplets, the droplets were generated on the 30×30 SiC-fiber lattice with a 4-mm lattice-point interval. The flame spread of the droplet cloud was initiated by the ignition of a droplet on one side of the lattice. We obtained unexpected findings from “Group Combustion” experiments. The mean droplet spacing of droplet cloud at the group-combustion-excitation limit obtained in “Group Combustion” experiments is greater than that predicted by the percolation model considering the local interactive effect. We observed two anomalous combustion phenomena near the group-combustion-excitation limit: a large-scale ignition of a droplet cluster [4), 10)] (Fig. 1) and re-burning by a slow flame propagation in a burned area [10)] (Fig. 2), which could contribute to the extension of the group-combustion-excitation limit. The observation for a droplet-cluster array with a backlight suggests that a cool-flame appears around a droplet cluster existing outside the flame-spread limit and the transition from a hot-flame to a cool-flame after the radiative extinction of the hot-flame although the cool-flame was not directly observed by a visible light video camera [10)]. Therefore, there is the possibility of a cool-flame appearance in both anomalous combustion phenomena. The results also suggest that there is the possibility of a cool-flame propagation over droplets.

The findings mentioned above motivated us to plan new experiments titled “"Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds-2 (Group Combustion-2)" to be conducted aboard Kibo to study the role of a cool-flame on the flame spread over droplet clouds. This project was accepted in 2019 as a feasibility study (FS) for on-orbit experiments aboard Kibo. This report describes an outline and the current state for “Group Combustion-2.”

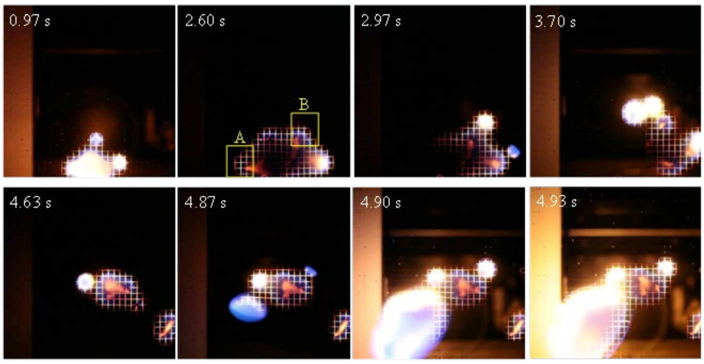


Fig. 1 Flame-spread behavior with a large-scale ignition for mean droplet spacing $(S/d_0)_m$=14.5 [10].

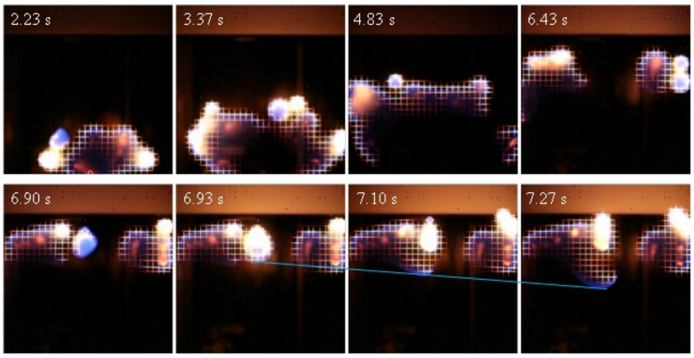


Fig. 2 Flame-spread behavior with a slow flame propagation in a burned area for mean droplet spacing $(S/d_0)_m$=13.3 [10].

2. Outline

In order to attain the research purpose of “Group Combustion-2”, we are planning to conduct the following four types of experiments aboard Kibo:

Exp. 1: Study of a cool-flame in the large-scale ignition and slow flame propagation in a burned area during the flame spread over randomly distributed droplet clouds

Exp. 2: Study of droplet-cloud elements to reproduce similar phenomena to those in Exp. 1

Exp. 3: Study of cool-flame propagation over droplets

Exp. 4: Study of a cool-flame and its effect on the flame spread over movable droplets

GCEM will be modified so that a cool flame is detected by the following four methods:

A: observation of a cool flame using an intensified camera with an optical interference filter

B: detection of a cool-flame using radiometers

C: detection of a cool-flame based on SiC fiber emission using a digital video camera without IR blockage filter

D: detection of a cool flame based on vaporization rate using a digital video camera with a back light

While a cool-flame occurs, formaldehyde emits a weak light with 370-470 nm. In Method A, we will identify a cool-flame through the observation of formaldehyde emission around a droplet using an intensified camera with an optical interference filter.

Combustion products of cool-flame, such as H_2O, CO_2 and CO, emit mid-infrared (IR) light. The US's on-orbit droplet combustion experiments titled FLEX detected the transition from a hot-flame to a cool-flame using radiometers measuring such an infrared light [11-13]. In Method B, we will detect a cool-flame using radiometers similar to FLEX experiments.

The gas temperature can be measured through the SiC-fiber temperature since the temperature of a fine SiC fiber tethering droplets quickly responds to the gas temperature change. The thin filament pyrometry (TFP) detects the fiber temperature based on the light emission from the fiber. While a hot-flame occurs, the flame temperature exceeds 1000 K and the SiC fiber emits a visible light. On the other hand, the cool-flame temperature is below 800 K at atmospheric pressure. The SiC fiber in the cool-flame does not emit visible light but infrared light. In Method C, we will detect near-infrared light from the SiC fiber using a digital video camera without IR blockage filter and identify a cool-flame based on the near-IR TFP.

The vaporization rate is measured through the droplet diameter measurement by a digital video camera with a back light. In the FLEX experiments, the vaporization rate decreases after the transition from a hot-flame to a cool flame [12-13]. In Method D, we will identify the vaporization with a cool-flame based on the vaporization rate.

3. Current state

In order to identify a cool-flame based on the four methods described in Section 2, we have considered remodeling of GCEM that a new intensified camera with an optical interference filter and radiometers are installed for Methods A and B, respectively, and the original digital video camera is replaced with a new one without IR blockage filter for Method C. A high-speed camera is originally installed in GCEM and will be used in Exp. 4 of "Group Combustion-2." It will be replaced with the intensified camera depending on the experiment. A mechanical shutter will close the lens of the intensified camera to prevent an image intensifier from damage by excessive light from a hot-flame while a hot-flame is expected to exist in the field of view shown in Fig. 3.

The backlight position during the combustion experiments is limited only in the left area with 30×146 mm of the fiber lattice shown in Fig. 3. The droplets are placed so that the cool-flame-expected area is on the backlight for Method D. The measuring area of the radiometers is expressed as a circle in Fig. 3, which includes a part of the cool-flame-expected area.

In parallel to the preparation of the on-orbit experiments, we have conducted preliminary microgravity experiments at drop facilities and numerical simulation. In the drop experiments, we measured the SiC-fiber temperature around a

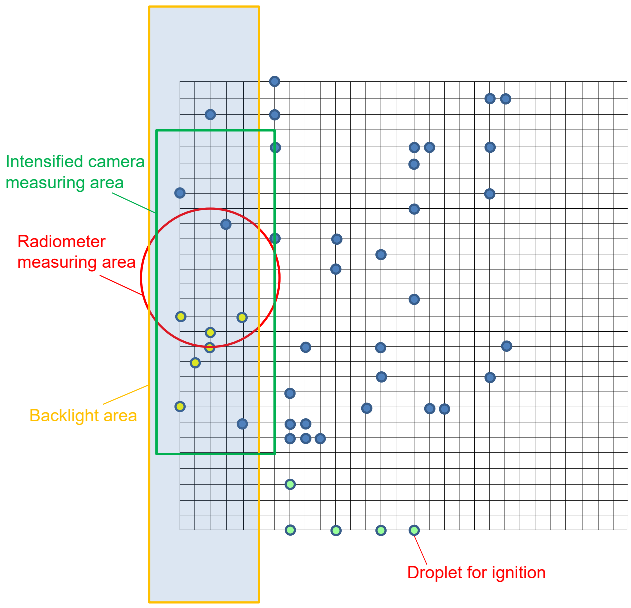
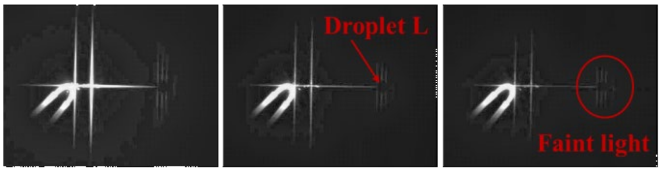


Fig. 3 An example of droplet cloud on the fiber lattice. The backlight area, intensified camera measuring area and radiometer measuring area for "Group Combustion-2" are also shown.

droplet during flame spread over droplet-cloud elements using an infrared camera and TFP. The results show that a 720-730 K region appears around a 0.5 mm *n*-decane droplet heated by a group flame surrounding interactive droplets at atmospheric pressure, suggesting that a cool-flame appears [14-15] (Fig. 4). The numerical model simulates a cool-flame appearance during flame spread over droplet-cloud elements considering the low-temperature chemistry.



t/d_0^2=1.68 s/mm^2 t/d_0^2=1.90 s/mm^2 t/d_0^2=2.09 s/mm^2

Fig. 4 Flame-spread behavior for S_{AL}/d_0=17 at 0.1 MPa (brightness level corrected) [14].

4. Concluding Remarks

We described the outline and current state of the FS of "Group Combustion-2." We will continue the preparation for it so that the FS will be completed at the end of FY2020 and on-orbit experiments can be started in 2022.

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