OR-0602

微小重力並行気流中でろ紙上に形成された火炎基部の消炎特性

Extinction Characteristics of Flame Base Formed on a Filter Paper in a Concurrent Flow under Microgravity Condition

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1. Introduction

For manned space missions, establishment of fire safety in spaceship and space station is important. In order to prevent occurrence of a fire in a closed and microgravity environment, clarification of spreading and extinction mechanisms of a diffusion flame formed on flammable solids under microgravity condition are necessary [1, 2]. Basically, the stability of a diffusion flame is determined by the behavior and structure of the flame base which locates at the most upstream portion of the flame. On the other hand, the flame spreading mechanism significantly changes depending on the direction of ambient oxidizer flow. When the flame spreading direction is opposite to the ambient oxidizer flow, the flame spreading phenomenon is called an opposed flow flame spread. For the opposed-flow flame spreading, heat transfer and combustion reaction in the flame base region determine not only the extinction limit but also the flame spreading rate. From scaling analysis, S. Takahashi [3] proposed the flame base model which could predict the flammability limits of a steady spreading flame on a thermally thin material in an opposed oxidizer flow under a microgravity condition. According to Takahashi's flame spreading model [3], the flame extinction occurs when the flame spreading rate becomes zero. When the flame spreading direction is along the ambient oxidizer flow, the flame spreading is called a concurrent flow flame spread. For the concurrent flow flame spreading, it is well known that the flame spreading rate is primarily controlled by heat transfer from the downstream region of the spreading flame and the combustion gas to the unburnt material. For the concurrent flow flame spread, the flame spreading rate exist even when the flame extinction occurs. Thus, in the concurrent flow flame spread, it is considered that the heat transfer and combustion reaction in the flame base region do not always have direct relation with the flame spreading rate like the opposed flow flame spreading.

In our previous study [4, 5], we carried out microgravity experiments of a concurrent flow flame spreading using a thermally thin filter paper and measured the flammability limits by changing an ambient flow velocity and an oxygen concentration in the oxidizer flow. From the experiment results, we verified the flammability map that showed U-shaped profile of the limiting oxygen concentration (LOC) and the existence of the minimum limiting oxygen concentration (MLOC). The flame spreading rate near limiting oxygen concentration, however, showed monotonically increasing tendency as the ambient flow velocity increased [5], which is different from the U-shaped profile of the limiting oxygen concentration. Thus, the flammability limits of the concurrent flow spreading flame was considered to depend on not the flame spreading characteristics but the extinction characteristics of the flame base. Therefore, in order to clarify the extinction mechanism of the concurrent flow flame spreading, we need to examine the behaviors of the flame base near the flammability limits in detail.

In this study, from analyzing the flame base behavior near the flammability limits, we will discuss and clarify the key phenomenon that is related to the extinction mechanism of the flame base.

2. Experimental apparatus and method

2. 1 Wind tunnel and microgravity experiments

The data of a concurrent flow flame spread in microgravity environment in this study were taken in parabolic flights carried out in 2018. Figure 1 shows the test section of the suction wind tunnel and the arrangement of recording devices [5]. The flow channel in the test section was 60 mm×70 mm×270 mm. The flow in the test section was driven by the pressure difference between inside and outside of the aircraft cabin. The cabin pressure was reduced to about 880 hPa in flight. The air flow velocity, U [cm/s], was calculated from dividing the air flow rate by the cross-sectional area of the test section. The oxygen concentration, X [vol.%], in the ambient oxidizer gas flow was reduced by adding a nitrogen gas from a high pressure gas cylinder to the cabin air and was determined from the ratio between the volumetric flow rate of the air and that of the nitrogen gas. A filter paper (ADVANTEC, No.4A) was used as a thermally thin flat sample, and its thickness was 120 μm. The sample width and length were 20 mm and 130 mm. The filter paper was attached to the sample holder with a metal tape and set at the center of the flow channel. Two digital video cameras were installed at the front and end sides of the wind tunnel. A coiled Kanthal wire (wire diameter 0.30 mm) was used for the ignition and heated electrically. An electrical current was supplied to the wire at 70 V and 3 A from a DC power supplier.

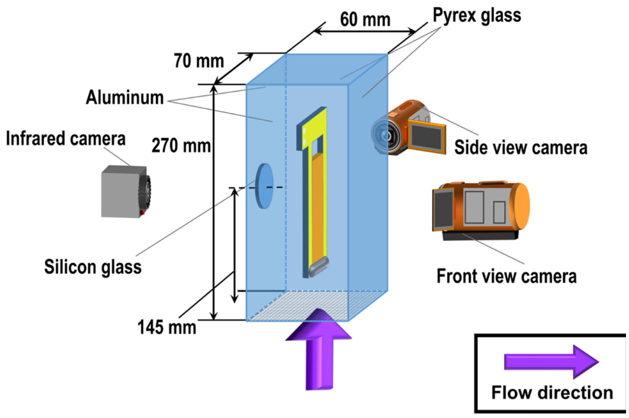

Fig. 1 Test section and the arrangement of recording devices

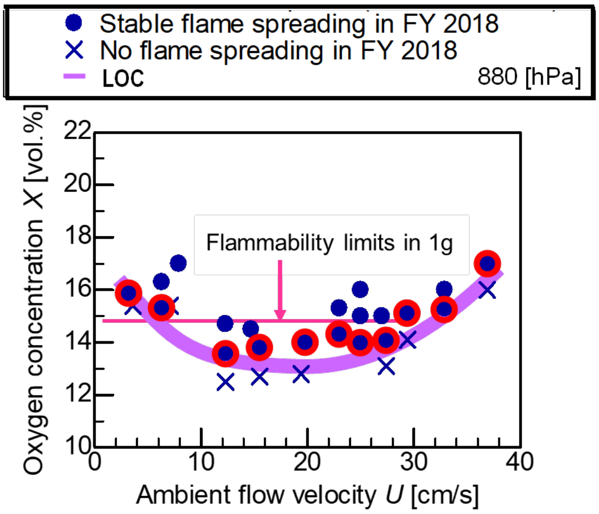

Fig. 2 Flammability diagram of the concurrent flow flame spread in microgravity environment

In the one parabolic flight, we had about 20 seconds test period. The procedure to measure the limiting oxygen concentration was as follows. First, the oxygen concentration was fixed at an arbitrary airflow velocity. Second, the filter paper was ignited under microgravity condition. When the flame did not spread from the ignition position or when the spreading flame was extinguished before consuming the whole paper sample during the microgravity period, the oxygen concentration value was considered to be below the limiting oxygen concentration. Therefore, the limit line of the oxygen concentration for the stable flame spread was drawn between the data point of flame spreading and that of no flame spreading.

2. 2 Flammability limits

Figure 2 shows a flammability diagram of the concurrent flow spreading flame in microgravity environment [5]. The relationship between the limiting oxygen concentration and the oxidant flow velocity indicates U-shaped curve, which is expressed by a thick purple line. The profile of the flammability limit is divided into three regions. Firstly, the flammability limit tends to decrease with increasing the airflow in the flow velocity range from 3.2 cm/s to 12.3 cm/s. Secondly, in the velocity range from 12.3 cm/s to 27.4 cm/s, the flammability limit shows almost constant value, which is considered to be minimum oxygen concentration. Thirdly, in the velocity range of the airflow more than 27.4 cm/s, the LOC value increases as the ambient flow velocity increases. The minimum value of the limiting oxygen concentration (MLOC) in this experiment is about 13-14 vol. %. The red circles shown in Fig. 2 indicate the combustion conditions close to the flammability limits.

2. 3 The positions of the pyrolysis front and the burnout end

The positions of the pyrolysis front and the burnout end in the concurrent flow flame spread near flammability limits were measured from the recorded images of the concurrent flow spreading flame. Each position was defined as shown in Fig. 3. The position of the pyrolysis front was the distance from the ignition location to the most downstream location of the pyrolysis region, and the position of the burnout end was the distance from the ignition location to the most upstream location of the pyrolysis region, at which the filter paper was burnt out completely. Figure 4 shows relationship between elapsed time after ignition in microgravity environment and the positions of the pyrolysis front and the burnout end. In The flame spreading rate was defined as the displacement speed of the leading edge of the pyrolysis region formed on the paper sample and was obtained from the relationship between elapsed time and the location of the leading edge of the pyrolysis region. The burnout progress rate was defined as the displacement speed of the rear end of the pyrolysis region and was acquired from the linear slop of the graph for the burnout end position in Fig. 4.

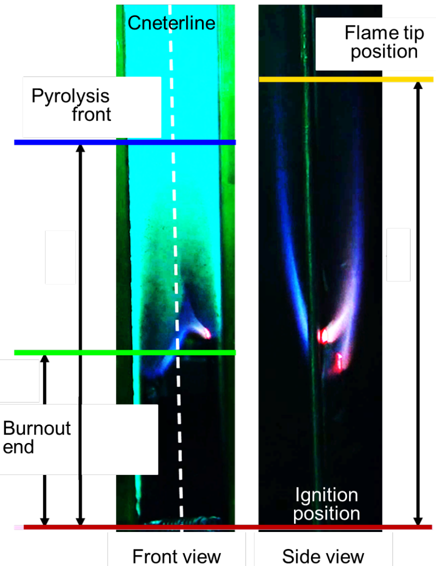

Fig. 3 Definitions for the position of the pyrolysis front and the position of the burnout end

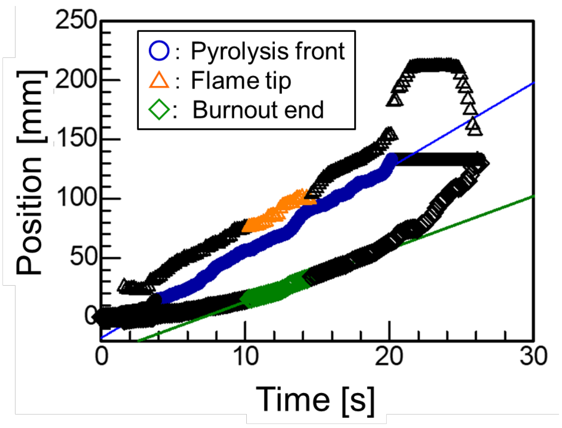

Fig. 4 Relationship between the positions of the pyrolysis front and burnout end and elapsed time (the ambient flow velocity: 15.5 cm/s and oxygen concentration: 13.8 %)

3. Results and Discussion

3.1 Flame spreading rate

Figure 5 shows the flame spreading rates of the diffusion flame in the concurrent flow near flammability limit under the microgravity condition. It is clear that the flame spreading rate increases linearly with increase in the oxidizer flow velocity. For an opposed flow flame spread, as the flame spreading becomes larger, the value of the limiting oxygen concentration decreases, that is, the opposed flow spreading flame is more difficult to be extinguished. Thus, for the opposed flow flame spread, there is a strong relationship between the limiting oxygen concentration and the flame spread rate. Therefore, Takahashi's spreading flame model that predicts the flammability limit based on the flame spreading mechanism is highly effective for the opposed flow spreading flame. When the ambient flow velocity is less than 10 cm/s, the concurrent flow spreading flame also shows the same tendency with the results of the opposed flow spreading flame. Therefore, in the range of the low flow velocity less than 10 cm/s, Takahashi's model is also considered to be effective for predicting the flammability limits.

However, when the ambient flow velocity is larger than 10 cm/s, the flame spreading rate of the concurrent flow spreading flame shows different trend from its flammability limits. The flammability limit shows almost constant and then increases as the flow velocity increases more as shown in Fig. 2. Therefore, for more than 10 cm/s, the extinction mechanism of the concurrent flow flame spread can not be explained from the flame spreading mechanism to determine the flame spreading rate.

3.2 Burnout progress rate

Figure 6 shows relationship between the burnout progress rate near the flammability limits and the ambient flow velocity. From the graph, it is found that the burnout progress rate does not indicate the same tendency with the flame spreading rate. The profile of the burnout progress rate is divided into three regions. Firstly, when the ambient flow is less than 12 cm/s, the burnout progress rate increases gently as the oxidizer flow velocity increases. The increasing trend of the burnout progress rate is the same as that of the flame spreading rate. Secondly, when the ambient flow velocity is from 12 cm/s to 24 cm/s, the burnout progress rate increases linearly, and the slop of the profile is larger than those in the other regions. In addition, the profile in the range of the ambient flow velocity includes an inflection point around the flow velocity of 20 cm/s. Thirdly, when the ambient flow velocity becomes larger than 24 cm/s, the burnout progress rate indicate constant value. As explained in the subsection 2.2, the flammability limit of the concurrent flow flame spread has the same tendency with that of the burnout progress rate. Thus, it is possible to say that for the concurrent flow flame spread, there is a strong relationship between the limiting oxygen centration and the burnout progress rate. Moreover, from examining the progress mechanism of the burnout end, that is, the flame base, there is a possibility to clarify the extinction mechanism of the concurrent flow spreading flame.

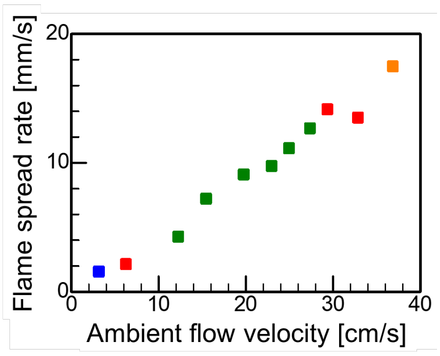

Fig. 5 Flame spreading rate near the flammability limits

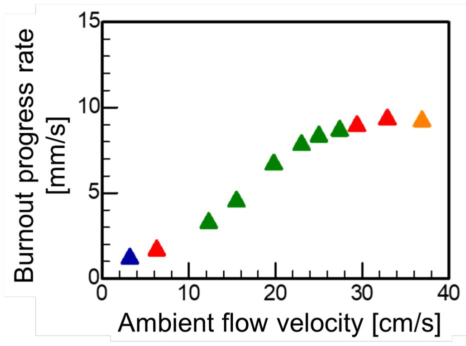

Fig. 6 Burnout progress rate near the flammability limits

4 Concluding Remarks

In this study, we have discussed the flame spreading phenomena formed over a thermally thin filter paper in the concurrent flow under microgravity condition. Especially, the flame spreading rate and the burnout progress rate near the flammable limit conditions are examined and these profiles as a function of the ambient flow velocity are compared with that of the flammability limit. As a result, the burnout progress rate shows the similar trend to the flammability limit. Therefore, through investigation of the progress mechanism of the burnout end, we might be able to clarify the extinction mechanism of the concurrent flow spreading flame in microgravity environment.

Acknowledgement

This study was performed in the FLARE project supported by JAXA. We are also thankful to the staff of Diamond Air Service for supporting parabolic flight experiments. I would like to express my gratitude to Ms. Makiko Fukuda, Tokyo University of Science., who had a great deal of cooperation in carrying out the experiments.

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