Horizontal flame spread along a thin paper-disk in a narrow space

Tadafumi Daitoku, Tomohiro Takahashi and Takashi Tsuruda
Akita Prefectural University
84-4 Ebinokuchi Tsuchiya,Yurihonjo, Akita, 015-0055 JAPAN

1 Introduction

Flame spread along combustibles is of interest in both fundamental research and fire safety. Flame spread is a complex problem that involves heat and mass transfer, fluid flow, and chemical reactions. Flame spread has been studied in various conditions, such as over liquids [1-7] and solids [8-11].

The smoldering of curing sheets sometimes occurs in factories and power plants. During maintenance work, a curing sheet is spread on the surface of the working area. A narrow gap between the sheet and the wall is often formed. If the sheet contacts a heat source, a fire may break out. When a fire occurs within a narrow gap, smoldering occurs due to a large amount of heat loss to the surroundings and an insufficient oxygen supply. It is important to understand the mechanisms of flame spread along a thin solid in narrow gaps.

Olson et. al. [12] reported finger-like smoldering patterns over a thin cellulose-based fuel with external airflow in microgravity. Zik et al. [13] and Uchida et al. [14] reported the fingering propagation along a thin solid in a narrow space with external airflow under normal gravity. They confirmed the influence of the Lewis number. Daitoku et al. [15-16] reported the relationship between the type of flame spread and the flame spread rate along a paper disk in narrow gaps. Some researchers speculate that the narrow space suppresses the buoyant flow and that an external airflow is needed to promote flame spread in a narrow gap. In this study, we experimentally investigated the effect of natural convection caused by a large temperature gradient on flame spread along a thin solid fuel in narrow gaps.

2 Experimental Apparatus and Method

Fig. 1 shows a schematic of the experimental apparatus. The experimental apparatus consists of a test section, an ignitor, digital video cameras, and an enclosure. The stage is made of granite stone that is 400 mm in diameter and 55 mm thick. The height of the stand is 100 mm above the floor. The enclosure removes airflow disturbances around the test section. The upper side of the enclosure is open in order to observe flame spread.

Correspondence to: daitoku@akita-pu.ac.jp

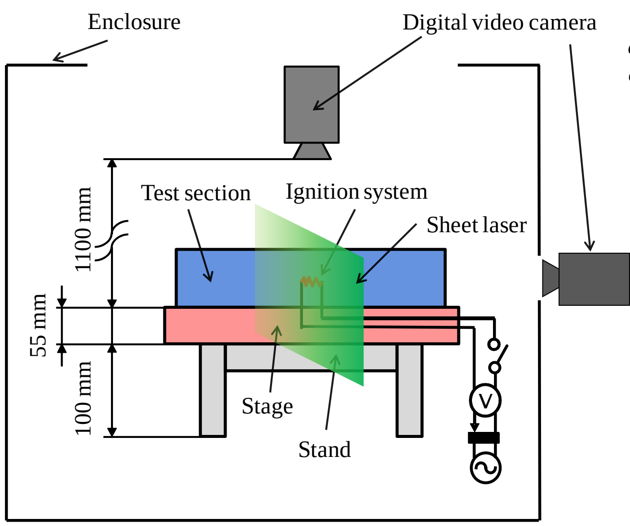


Fig. 1. Schematic of experimental apparatus

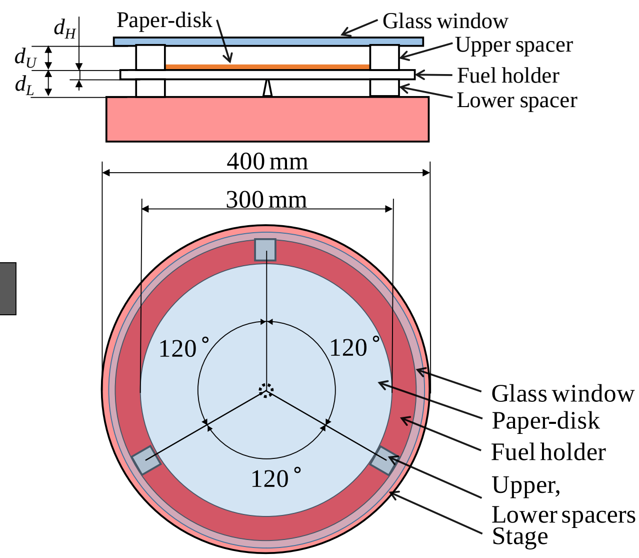


Fig. 2. Diagram of test section

Fig. 2 shows detailed top and side views of the test section. The test used fuel was a sheet of disk-shaped homogeneous filter paper (ADVANTEC, No.1), 300 mm in diameter. The two ring-shaped fuel holders used are 360 mm in outer diameter and 280 mm in inner diameter. One fuel holder consists of calcium silicate board with a thickness of 4.5 mm. To observe the flow near the fuel surface, a thin holder consisting of mica board 1.0 mm thick is also used. As described below, there was no influence on the flame spread and the flow due to the holder thickness. The filter paper was fixed on a fuel holder at 16 points using double-stick tape with uniform tension. The top panel, which forms a gap above the fuel, is a glass window for vertical observation. The glass window is 400 mm in diameter and 2.0 mm thick. The fuel holder is placed between the base and the glass window with spacers to maintain a constant gap. The length d_L gives the gap between the base and filter paper, the length d_U the gap between the glass window and filter paper, and the length d_H the holder thickness. A coil-like chromel thin wire is installed on the center of the base for ignition. The coil is about 3.5 mm in diameter. Electrical heating is applied until the flame travels 15 mm from the center. The flame spread along the filter paper was recorded by a digital video camera from above. A close-up lens camera was used to record laser illuminated particles near the spreading flame. The obtained image was analyzed using image processing.

3 Results and Discussion

3.1 Category of the flame spread

Fig. 3 shows images of the typical course of flame spread observed in this study. The observed flame spreads are broadly categorized into three types. Fig. 3a shows uniform flame spread, fig. 3b shows flame quenching, and figs. 3c-e show non-uniform flame spread. The uniform flame spread is denoted as mode A, flame quenching is denoted as mode B, and non-uniform flame spread is denoted as mode C.

Particularly, the flame spread shown in fig. 3e is known as "fingering." In the case of the irregular flame spread observed in mode C, dense smoke was observed.

A white panel ring holds the paper disk, and flame spreads from the center of the paper disk. A hole is formed on the center of the paper disk after ignition, and the base becomes visible. Lines seen on the base are copper foils for power supply to the ignition source. The thickness of the copper foils is 0.1 mm, so no influence on the flame spread was observed. As mentioned above, in mode B, the flame was quenched and a part of the paper disk remained. In modes A and C, the flame eventually reached the holder ring. Furthermore, there was no correlation between a given point on the filter paper and the direction of fingering.

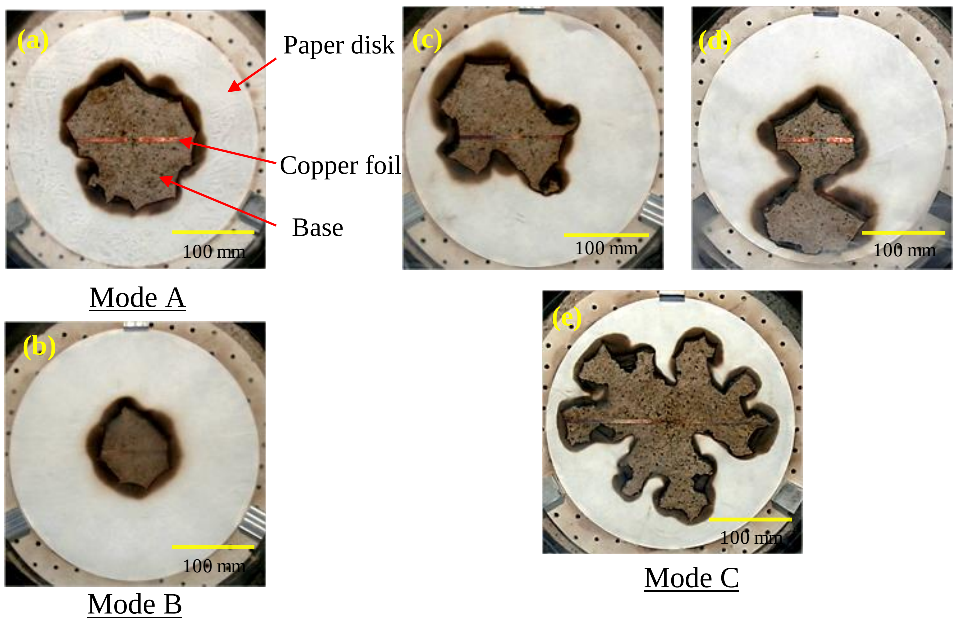


Fig. 3. Images of the typical course of flame spread[15-16]

3.2 Relationship between flame spread type and flame spread rate

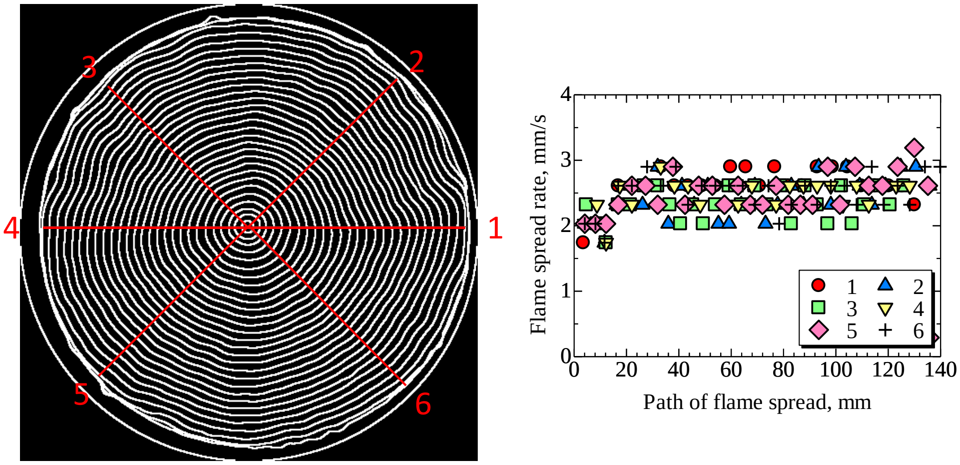
Figures 4-6 show the contour maps of leading edge of flame every 2 seconds. Flame spread rate was calculated on lines 1-6. Figure 4 shows that concentrically flame spread in mode A. Flame spread rate is almost constant about 2-3 mm/s in fig.4(b).

Figure 5 shows flame deceleration and extinction during the flame spread about 30 - 40 mm from the center.

Figure 6 shows the uniform flame spread in region A and the local extinction of propagating flame outside of region A. The flame accelerates and lareger fluctuation out of region A along lines 1-6.

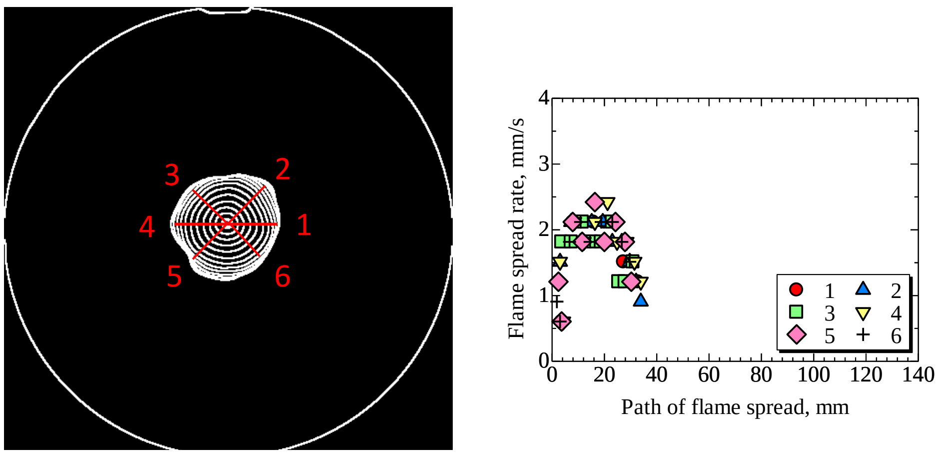
In our previous research [16], smoke movement in the vertical cross section through the center of the paper-disk was observed. The smoke rises from the ignition source, and expands outwards under the glass window. Smoke near the outer edge descends rapidly, and vortices of smoke form that gradually spread in the horizontal direction.

In this research, The air flow along the filter paper surface visualized using silica particle and a laser in the flame spread. In the lower part of the upper gap, the particles flow along the surface of the paper disk to



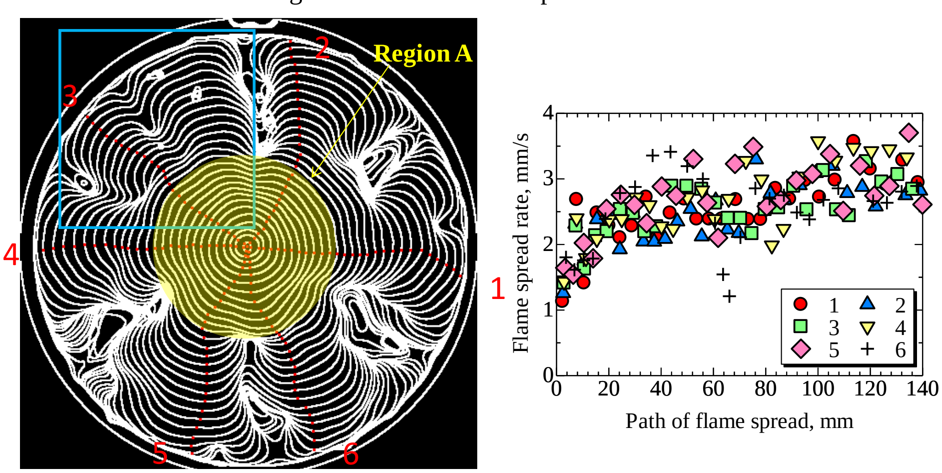
(a) Contour maps of leading edge of flame (b) Flame spread rate

Fig. 4. Horizontal flame spread of mode A



(a) Contour maps of leading edge of flame (b) Flame spread rate

Fig. 5. Horizontal flame spread of mode B



(a) Contour maps of leading edge of flame (b) Flame spread rate

Fig. 6. Horizontal flame spread of mode C

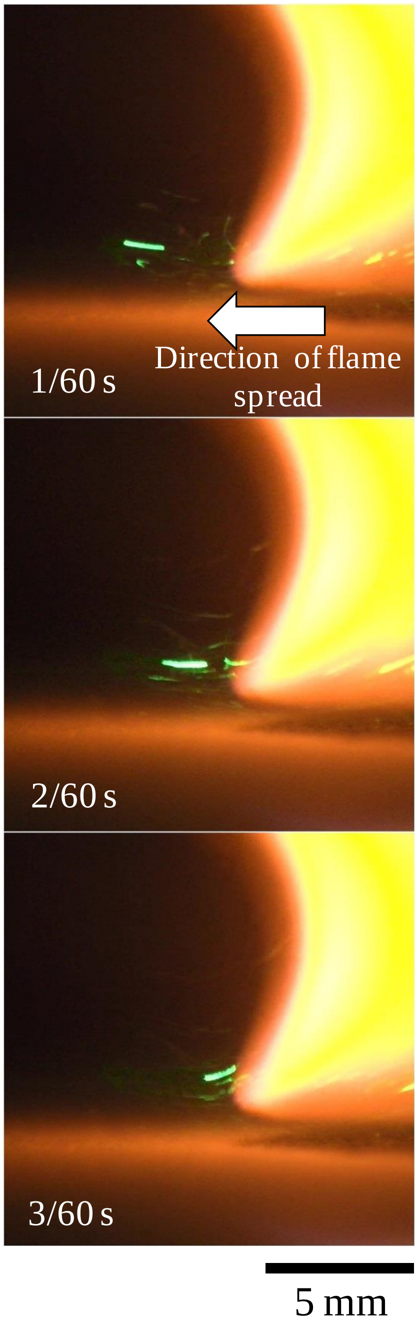


Fig. 7. Visualization of flow by using PIV technique in the upper gap

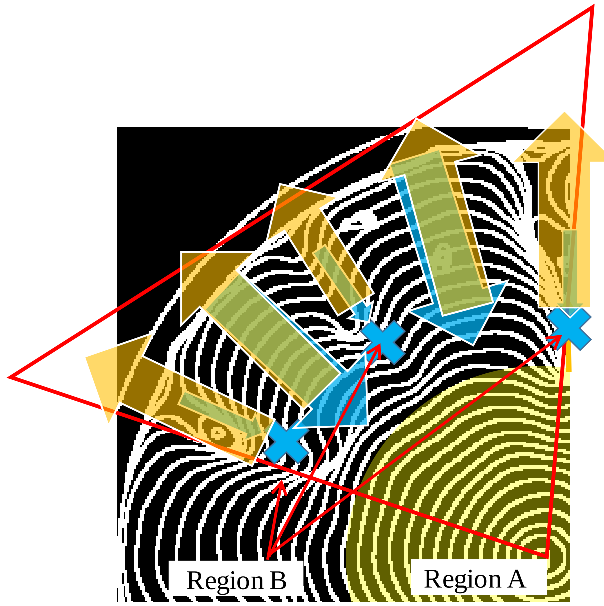


Fig.8. Relationship between leading edge of the flame and flow

the leading edge of flame as shown in figure 7. When particle reached leading edge of flame, the particles soared upward. The velocity of particles toward the flame was about 0.1 m/s.

It seems that, in the lower part of the upper gap, fresh air flows along the surface of the paper disk and the burnt gas flows out.

Flame spread continuously when the fresh air is supplied from outside and the burnt gas is discharged to outside of the upper gap. Fingering occurs when the fresh air is supplied insufficiently for uniform flame spread.

Figure 8 shows the region surrounded with a square on figure 6 (a). The blue arrowhead shows the fresh airflow and the orange arrowhead shows the burnt gas flow. Before fingering occurs, the fresh air is supplied uniformly along filter paper to the inner flame and the volumetric expansion is small due to the small flame length in Region A. The diverging flow is slow enough to achieve a uniform velocity distribution. However, when leading edge of flame reached region B, the volumetric expansion exceeds the uniform divergent flow limit and non-uniform flow appears. The net oxygen supply to the local flame front decreases where the burnt gas flows.

4 Conclusion

The objective of this study was to obtain fundamental knowledge of the flame spread characteristics of thin solid fuel in narrow gaps, focusing on the behavior of the flame and the effect of the narrow gap between two plates, experimentally. The results obtained are

(1) The flame fronts of mode A and C are observed horizontally with contour maps to examine the growth of fingers.

(2) The growth of fingers occurs in the later stage of the flame propagation.

References

[1] I. Glassman, J. G. Hansel, and T. Eklund (1969). Hydrodynamic effects in the flame spreading, ignitability and steady burning of liquid fuels. Combust. Flame 13(1) :99.

[2] K. Akita and O. Fujiwara (1971). Pulsating Flame Spread along the Surface of Liquid Fuels. Combust. Flame 17(2) :268.

[3] K. Akita (1973). Some problems of flame spread along a liquid surface. Proc. Combust. Inst. 14 :1075.

[4] T. Hirano, T. Suzuki, I. Mashiko, and N. Tanabe (1980). Gas Movements in Front of Flames Propagating Across Methanol. Combust. Sci. Technol. 22 :83.

[5] R. Mackinven, J. G. Hansel, and I. Glassman (1970). Influence of Laboratory Parameters on Flame Spread Across Liquid Fuels. Combust. Sci. Technol. 1(4) :293.

[6] F. J. Miller and H. D. Ross (1998). Smoke visualization of the gas-phase flow during flame spread across a liquid pool. Proc. Combust. Inst. 27(2) :2715.

[7] H. D. Ross and F. J. Miller (1998). Flame spread across liquid pools with very low-speed opposed or concurrent airflow. Proc. Combust. Inst. 27(2) :2723.

[8] J.N. De Ris (1969). Spread of a laminar diffusion flame. Proc. Combust. Inst 12(1) :241.

[9] A.C. Fernandez-Pello, F.A. Williams (1975). Laminar flame spread over PMMA surfaces. Proc. Combust. Inst. 15(1) :217.

[10] A.C. Fernandez-Pello , S.R. Raya, I. Glassman (1981). Flame spread in an opposed forced flow: the effect of ambient oxygen concentration. Proc. Combust. Inst. 18(1) :579.

[11] T. Hirano, K. Sato, Koichi Tazawa (1976). Instability of downward flame spread over paper in an air stream. Combust. Flame 26 :191.

[12] S. L. Olson, H.R. Baum, T. Kashiwagi (1998). Finger-like smoldering over thin cellulosic sheets in microgravity. Proc. Combust. Inst. 27 :2525.

[13] O. Zik, E. Moses (1998). Fingering instability in solid fuel combustion: The characteristic scales of the developed state. Proc. Combust. Inst. 27 :2815.

[14] Y Uchida, K Kuwana, G Kushida (2015). Experimental validation of Lewis number and convection effects on the smoldering combustion of a thin solid in a narrow space. Combust. Flame 162 :1957.

[15] T. Daitoku, T. Takahashi and T. Tsuruda (2015) Flame Spread along a paper disk in a narrow channel. Proc. ICDERS. 25 :PI-39.

[16] T. Takahashi, T. Daitoku and T. Tsuruda, Behavior of the flame spread along a thin paper-disk in a narrow space. Proc. Combust. Inst. In press.