Rise and Fall of Vortex on a Rotating Paper

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1 Introduction

In large-scale fires, fire whirl spreads in a short time. The reports on fire whirls after the Great Kanto Earthquake on September 1, 1923 describe that large fire whirls spread at Hifukusyo-ato and killed a large number of evacuees [1–3]. The open place called Hifukusyo-ato was the east of the Sumida river and surrounded by buildings. Fire whirls spread from three directions to the open space. Presuming a large vortex at the open space, flame spread from the outer edge of the open space. Reports say that fire whirls appeared near the burning area, the rotation directions of fire whirls were not constant, and they traveled in the open space. These observations show that flow vortex and heat source travel as fire whirls.

Under most experimental conditions, a fixed heat source is employed.

The flame spread in a vortex is of interest for both fundamental research and fire safety applications on fire whirl. Rise and fall of vortices during flame spread is a complex problem that involves heat and mass transfers in the boundary layer.

Rise of vortices is much more likely to occur in circulating flows [4].

The thickness δ of boundary layer on the ground under rotating flow of a angular velocity ω for a kinematic viscosity ν by Boedewadt [4] is

$$\delta = 8(\nu/\omega)^{\frac{1}{2}} \tag{1}$$

Equation(1) shows that the thickness of boundary layer on the ground of rotating flow 10 rad/s is 3 mm for the kinematic viscosity ν of air. The thickness of boundary layer δ decreases as the angular velocity ω increases. The roughness of ground should be less than the thickness of boundary layer. The interaction of natural convection and rotating flow could be examined with a model scale of 0.1 m.

In fire whirls, thermal convection is present in these circulating flows. The heat released from the flame generates a natural convection in income flow.

Most of work on fire whirls has used liquid fuel pool with various circulating flows [5–7]. This experimental configuration gives a fixed heat source and traveling vortex.

Recently, experimental studies on fire whirls shows boundary layers near the burning pool [8, 9]. These studies have shown that position of the liquid pool must be adequate in order to stabilize a whirl. Fire whirls generally occur near the burning area and the relative position of circulating flow area changes with time.

In this study, flame spread in a well-defined circulating flow on a rotating paper disk was examined with video images.

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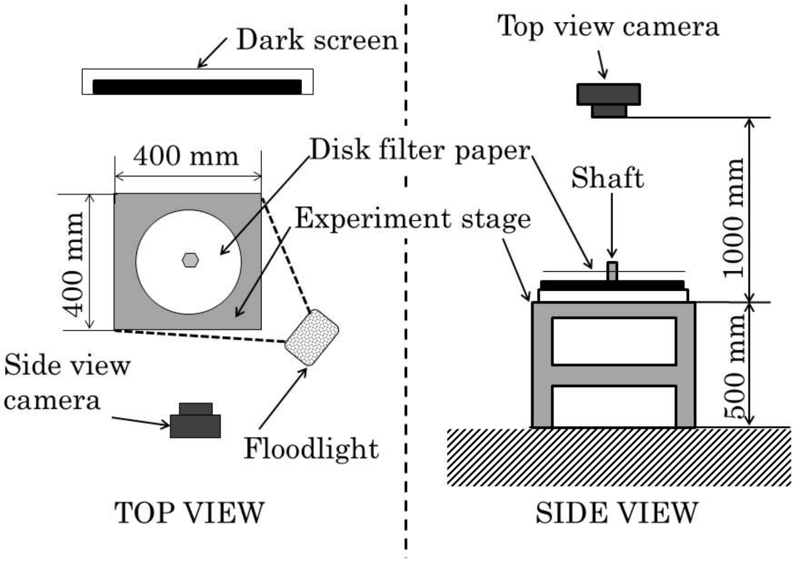

Figure 1: Experimetal Apparatus

2 Experiment

2.1 Experimental Apparatus

A 400 mm square of experiment stage is 500 mm above the floor. A disk filter paper of 240 mm in diameter fixed on a stepper shaft from 40 to 50 mm above the experimental stage in the horizontal plain. Angular velocities are 9.4 rad/s and 12.6 rad/s.

Two video cameras recorded flame spread from the top and side of the disk filter paper. A floodlight illuminated the paper to maintain the short exposure time. A dark screen was used for the background of side-view. The top-view camera is 1000 mm above the experiment stage near the exhaust duct opening to minimize the deformation of image due to inclined view. The frame rate of the top-view camera was 600 frames/s to capture the high-speed flame movements. Recorded images were store in a flash memory card and processed on PCs. Eight marker lines divide the disk filter paper in eight sections.

A circular fuel tray of 2 mm wide, 3 mm deep trench in 240 mm diameter filled with ethanol on the experiment stage stabilizes a circular flame for heating the rotating filter paper uniformly. Using this configuration, uniform ignition along the circumference of filter paper is achieved. Ethanol flame burns about 8 seconds. The mass density of the disk filter paper of ADOVANTEC No.2 is 125 g/m^2. The thickness of filter paper is 0.26 mm.

2.2 Experiment Procedure

After the angular velocity of the disk filter paper achieving the scheduled value, a gas flame ignited ethanol in the circular tray at t = 0. Flame heated the rim of disk filter paper uniformly. Its surface turned from white to black through dark brown as the flame spreads.

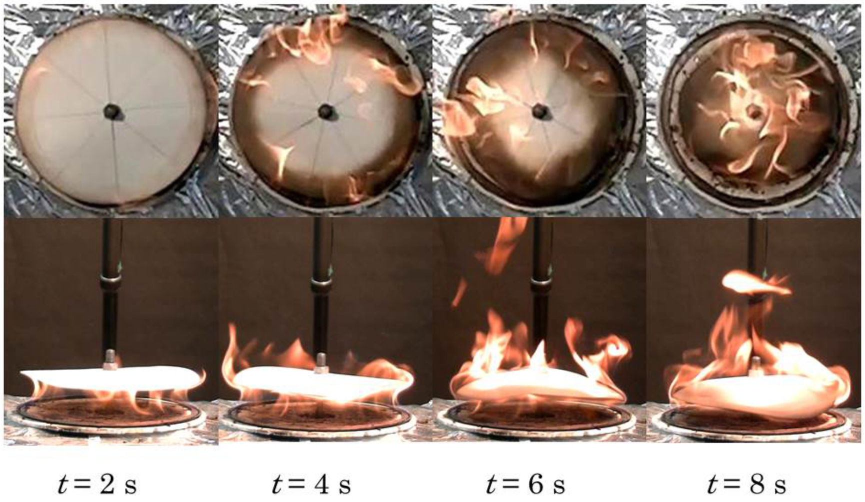

Figure 2: Top and Side Views of Observed Flame

3 Results and Discussion

3.1 Video Image

Figure 2 shows top and side views of flame and pyrolysis zone of an experiment at t = 2, 4, 6, 8 s. The pyrolysis zone spread from the rim of disk filter paper after t = 4 s. Flames are seen near the pyrolysis zone at t = 8 s in the side view. Flame inclines due to the inward flow induced by the natural convection. Various curved flames appear at t = 8 s in the top view, when the disk filter paper becomes hemispherical due to non-uniform shrinking between the upper and lower surfaces of filter paper.

3.2 Flame and Pyrolysis Zone

The fresh surface of paper reflects light to nearly saturated brightness level with the short exposure time at 600 frames/s. As flame spread along the disk filter paper, the brightness of paper decreases to the dark level. Red component at flame increases above that of paper. The obtained flame and filter paper locations are shown in figures 3,4 with time. Black dots in fig. 3 is flame, white area in fig. 4 is fresh surface of paper. Flame appears after t = 2 s. Flame from the tray is seen from t = 2 to 3 s. The spreading flame appears after t = 4 s. The mean flame location moves inward with the pyrolysis zone. Detected flame area becomes the minimum value at t = 5 s.

The pyrolysis zone spread after t = 2 s and the zone reached the fixing nut at t = 8 s. Dividing the radius by a travel time Δt = 6 s, the mean spread rate is 20 mm/s. This rate is several times larger than that of horizontally spreading flame along filter paper with line ignition. The linear line in this figure shows that the flame spread rate is constant during this experiment.

The ethanol flame is seen at r = 120 mm. Curved flame deformed by vortex is seen moving at a low speed near pyrolysis zone. The schematics of observed vortices are shown in figure 5. The central vortex rotates toward the same direction with the paper. Periphery vortices rotate oppose to the central vortex rotation. For

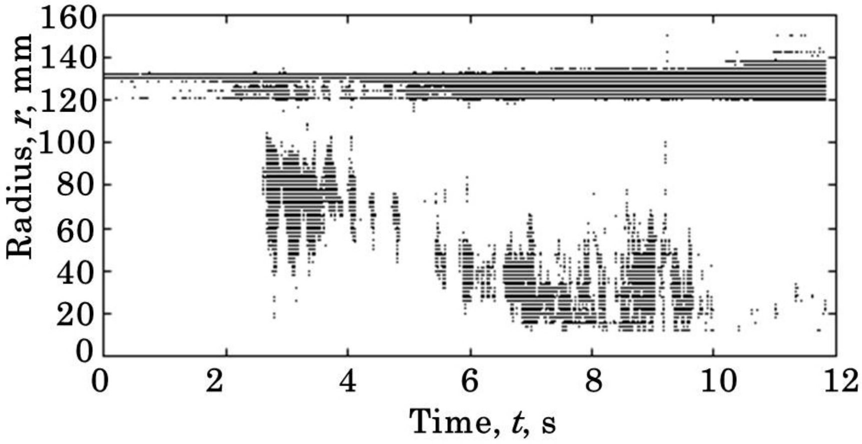

Figure 3: Flame Locations

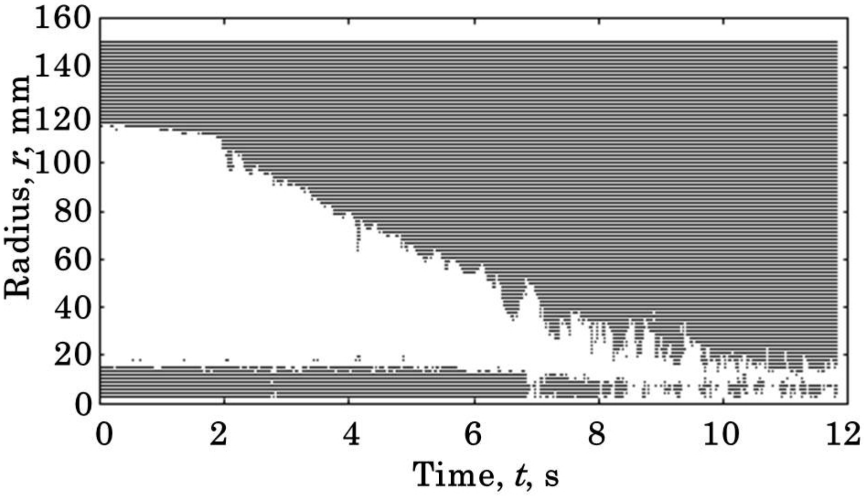

Figure 4: Fresh Filter Paper Location

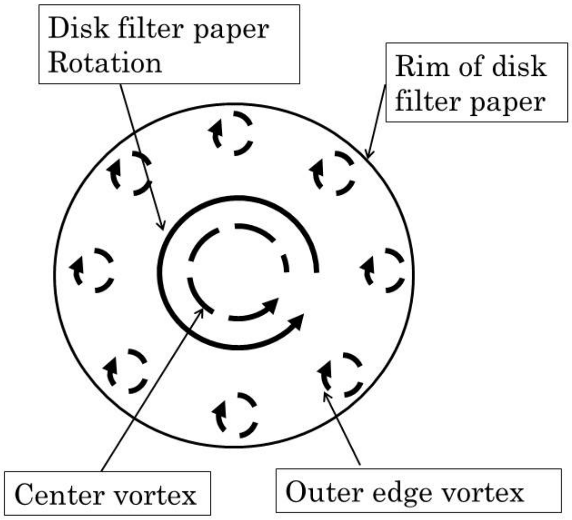

Figure 5: Schematics of Observed Vortexes

a simple case of two vortices with strength Γ_1,Γ_2 and a separation r_{12} [10, 11] in non-dimensional form,

$$-\frac{\Gamma_1\Gamma_2}{2\pi}\log(r_{12}) = const \tag{2}$$

If the strengths of vortices are constant, two rotate with a separation. There are two types of vortex pair movements, rotational and parallel. If the strength of central vortex is Γ_1 and that of outer one is Γ_2, this pair rotates and the outer vortex goes through the pyrolysis zone to form curved flame.

For cases of more than three vortices, their movement is complicated [12]. If two vortex appears near the ground, there are two trajectories, rotational and parallel ones. One of vortex goes through the pyrolysis zone and curved flame appears as fire whirl. If the movement of fire whirl controlled by the vortex pair, the relative position and movement of this fire whirl is determined by the strength and initial separation of vortices.

3 Conclusion

Flame spread along a rotating disk paper was examined with a high-speed video camera. Curved flame appears when the rotating vortex is going through pyrolysis zone. Using a flat filter paper rotating a constant angular velocity, interacting vortices forms fire whirl near the pyrolysis zone.

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