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Paper

Flame Propagation in Counter Airflow along the Ground Soaked with High-Volatile Liquid Fuel

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Abstract

Flame propagation in a layered flammable gas mixture along the fuel-spilled ground was studied experimentally. The behavior of flame tip was investigated by simultaneous measurements of the images by color Schlieren photography and by chemiluminescence zone due to OH radical in the flame tip. The effects of ground conditions; the surface inclination, the ground temperature and the counter airflow velocity, on the propagation velocity of flame tip and on the thickness of flammable gas layer were examined. The thickness and the length of OH luminescence zone in the flame tip were in the order of 1 and 2~3 cm respectively. The tip of OH luminescence zone propagates in the velocity boundary layer of the counter airflow along the fuel-spilled ground. When the ground temperature is not so high, even over the stoichiometric temperature of the liquid fuel, no propagation of flame tip occurs in the counter airflow of which the velocity is over the flame propagation velocity without the airflow. This is mainly due to the decrease in the rate of formation of flammable gas layer on the unburned ground, which is in contrast to the flame propagation along the liquid pool surface in an opposing airflow.

Keywords : Flame propagation, OH radical, Fuel-soaked ground, Counter flow, Flammable layer.

1. Introduction

On the ground soaked with highly volatile liquid fuel, if the ignition occurred by some heat source, the flame propagates with high velocity through the layered flammable gas mixture on the ground. The ground surface will thus be, in general, covered with flame in a very short time. The flame propagation is, of course, affected strongly by the rate of formation of flammable gas layer with concentration gradient [1~15, 20]. The flame spread is, however, relatively slow on the ground of which the temperature is under the stoichiometric temperature of the combustion of spilled liquid fuel [12~15].

When the ground temperature is near the stoichiometric temperature we can see the small tip of pale precursor flame traveling along the surface before the steady spread of flame. The travelling small flame tip vanishes at the end of fuel-spillage area, and thus the ground surface is not covered with flame. When the ground temperature is over the stoichiometric temperature, however, the flame propagation is very fast and the ground is to be covered with large flame in a very short time [14]. Consequently, the behavior of the precursor flame tip must be affected strongly by the conditions of formation of flammable gas layer ; air stream along the ground, inclination angle of ground surface and the temperature of ground [16~20]. The present study aims to clarify the behavior of the small precursor flame tip in a flammable gas layer by using a visualization technique of the reaction zone in the flame during its high speed propagation in the counter airflow along the ground surface.

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2. Apparatus and Procedure

Figure 1 shows the experiment setup of this study, where the simultaneous measurement system of Color Schlieren photography and of chemiluminescence zone image in the flame tip are shown. The stainless tray (50mm in width, 400mm in length, 15mm in depth) filled with glass beads (0.1mm in dia.) was used as the model of ground, and the temperature of glass beads bed was controlled. N-octane was used as the spilled liquid fuel.

The glass beads bed was set in the counter airflow (from 0 to 150cm/s) from the rectangular outlet (125 x 125mm) of well rectified wind tunnel. The chemiluminescence image due to OH radical in the flame tip was monitored through the band pass filter (Central-peak wavelength ; 307.6nm, Half-peak width; 10nm), and the image intensified CCD Camera (Shutter speed was fixed as 1/1500sec by pulse generator). Preceding the glass beads bed, a starting plate (180mm from the exit) was set. The inclination angle of the tray with the starting plate was set from 0 to 20 deg.

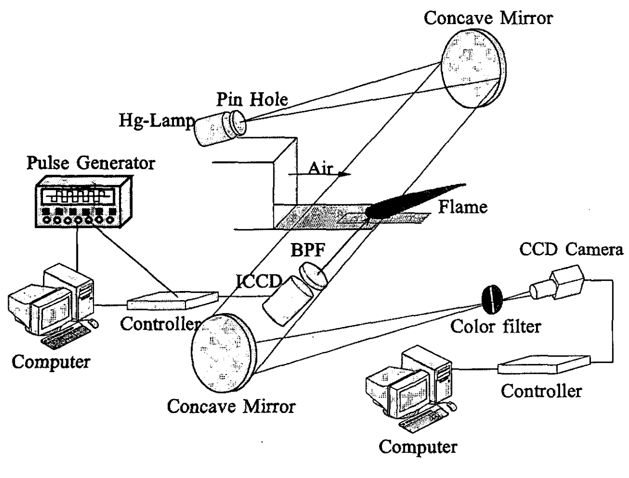

Figure 1 : Experimental Setup

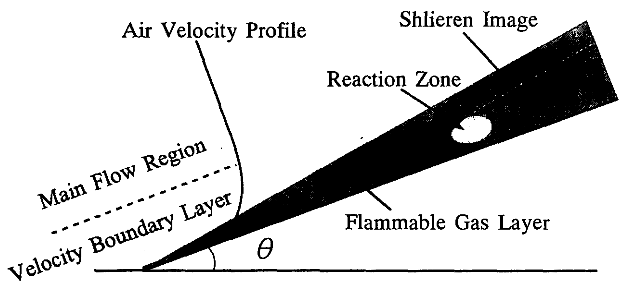

Figure 2 : Schematic Illustration of the Flame Propagation

The schematic illustration of the flame propagation through the layered flammable gas mixture in the counter airflow along the beads bed surface is shown in **Figure 2**. The velocity of counter airflow was measured by a heat ball type (2mm in dia.) airflow meter. The thickness of flammable gas layer was measured by the image of color schlieren photography.

3. Results and Discussion

The typical velocity profiles of the counter airflow along the beads bed surface are shown in **Figures 3 and 4**. From these velocity profiles, we can see that they are nearly the same and affected by neither the inclination angle nor the distance from the edge of the beads bed end in the present experimental condition. As we can predict, the thickness of flammable gas layer will decrease with increase in the velocity of counter airflow, and increase with increase in the temperature of beads bed.

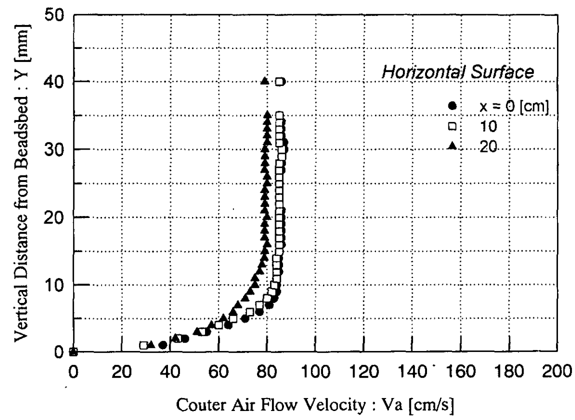

Figure 3 : Effect of the Distance from the Beads Bed Edge on the Velocity Profile of Counter Airflow

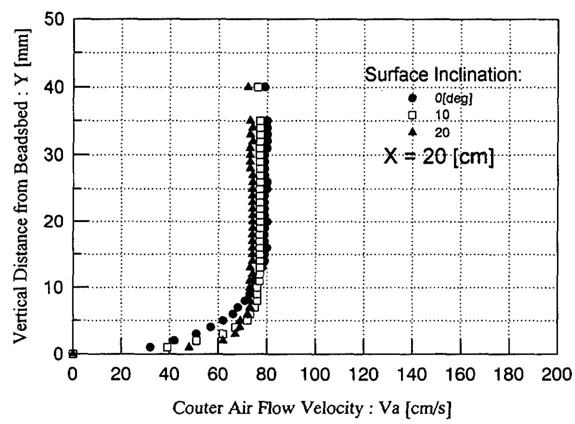

Figure 4 : Effect of the Inclination Angle on the Velocity Profile of Counter Airflow

Figures 5 and 6 show the thickness of layered flammable gas affected by the airflow velocity and by the inclination angle. From the results in these figures, we can see that the thickness of layered flammable gas is under 10mm and is not dynamically affected by the counter airflow and by the inclination angle of ground surface in this study.

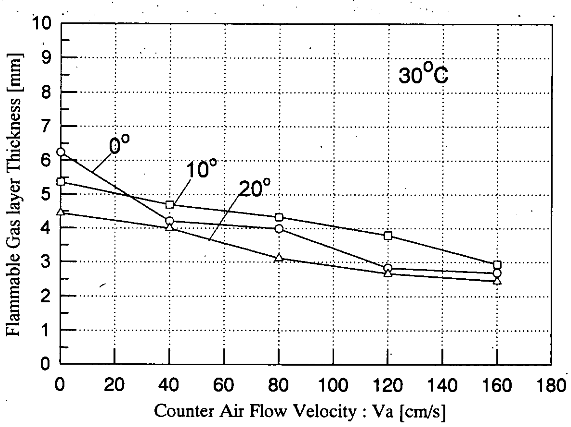

Figure 5 : Thickness of Flammable Gas Layer vs. Velocity of Counter Airflow

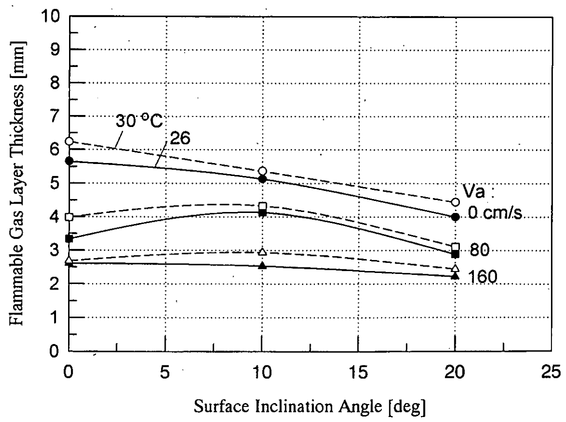

Figure 6 : Thickness of Flammable Gas Layer vs. Surface Inclination Angle

Typical images of OH luminescence zone in the flame tip and of Schlieren photography are shown in **Figure 7**, where we can see that both of OH zone and Schlieren images have the same shape at the flame tip.

Although flame propagation in an air stream along a liquid and/or solid surface has been very important (and interesting) subject of study from the point of view of fire hazard prevention, only a few papers on the study have been reported. We can see some excellent pioneering works by Suzuki and Hirano [10, 16, 17] on the study of flame spread along liquid

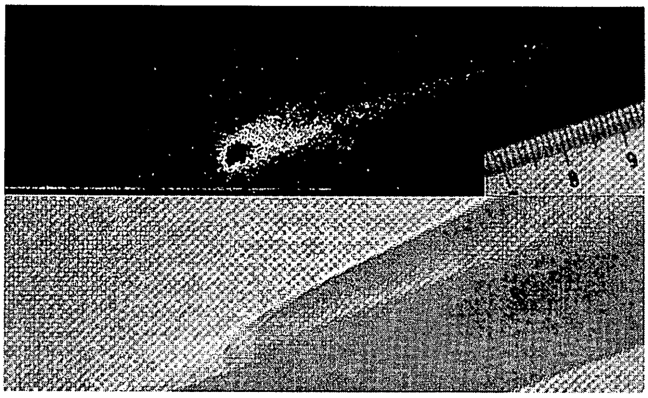

Figure 7 : Typical Images of OH Luminescence Zone in the Flame Tip (Upper) and of Schlieren Photography (Under). Beads Bed ; 25℃, Inclination ; 20°, Airflow; 45cm/s.

pool in an air stream.

Figures 8 and 9 shows the spread velocities of the OH zone on the ground surface affected by the inclination angle and by the velocity of counter airflow.

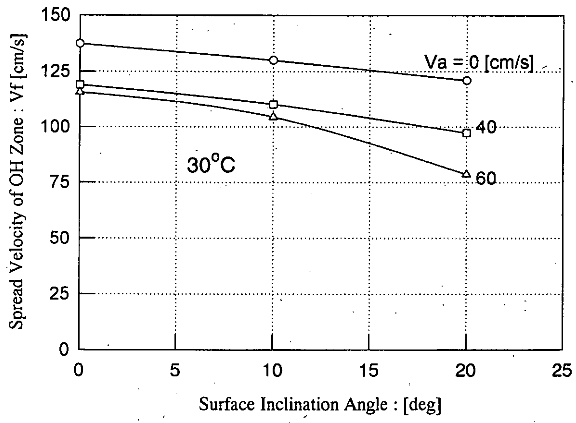

Figure 8 : Spread Velocity of OH Zone vs. Surface Inclination Angle

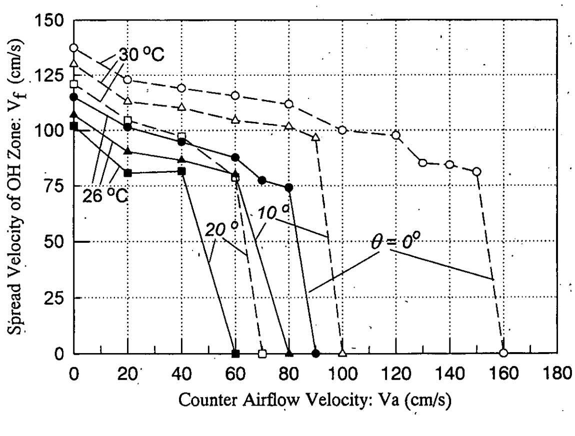

Figure 9 : Spread Velocity of OH zone vs. Velocity of Counter Airflow

When the ground temperature is considerably higher than the stoichiometric temperature, horizontal flame propagation occurs even in the counter flow of which the velocity is over the flame propagation velocity without the airflow. This is due to the thickened layer of flammable gas mixture. Although the spread velocity decreases moderately with increase in the surface inclination, we can see the clear effect of buoyancy on the downward flame propagation along the inclined surface. With increase in the velocity of counter airflow the propagation of flame tip becomes very unstable. Along the inclined ground surface and/or when the ground temperature is not so high, even over the stoichiometric temperature of spilled liquid fuel (about 23.5℃ for n-Octane), no propagation of the flame occurs in the airflow of which the velocity is over the flame propagation velocity without counter airflow. This is in contrast to the result shown in the previous study on the flame propagation along the methanol pool in an opposing airflow [10]. Suzuki and Hirano showed that the flame can propagate along the pool surface without a remarkable decrease in the velocity even in the opposing airflow of which the velocity is much higher than the flame propagation velocity without the airflow.

The clear difference in the critical velocity of opposing airflow to prevent the flame propagation will be attributable to the low rate of formation of flammable gas layer on the unburned ground surface. To form the flammable gas layer on the ground, the fuel must be transported onto the surface by capillary rise and/or vaporization. The thickness of flammable gas layer decreases with increase in the counter airflow as shown in **Fig. 5**.

The length and the thickness of the OH luminescence zone are defined as shown in **Figure 10**. The dark area surrounded by bright green zone shows the strong luminescence due to OH radical concentration in the flame tip. The thickness and the length of the OH strong luminescence zone are shown in **Figures 11 and 12**.

We can see that the thickness of OH zone, less than that of the velocity boundary layer, increases clearly when the beads bed temperature is over the stoichiometric temperature of the combustion of n-Octane. This is due to the increase in the thickness of the layered flammable gas on the surface. The thickness of OH zone decreases clearly with increase in the velocity of counter airflow, which is attributable to the decrease in the thickness of flammable gas layer. Compared with the effect by the temperature of beads bed, the velocity of counter airflow has less conspicuous effect on the length of OH zone. The

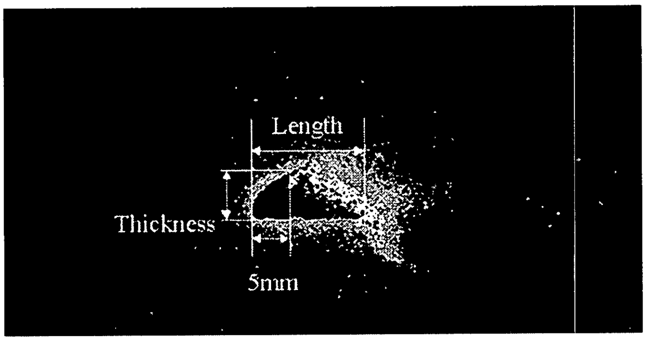

Figure 10 : The Thickness and the Length of OH zone

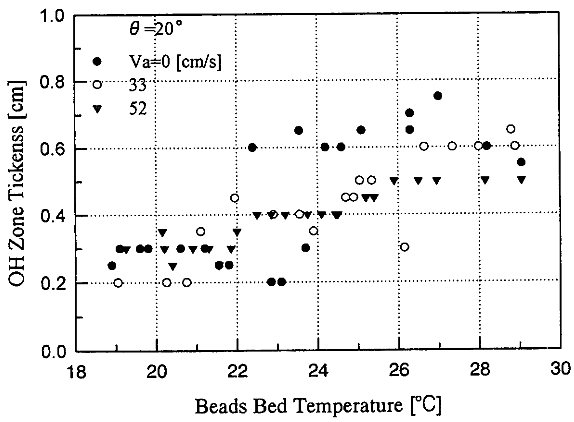

Figure 11 : Effect of Beads Bed Temperature on the Thickness of OH Luminescence Zone

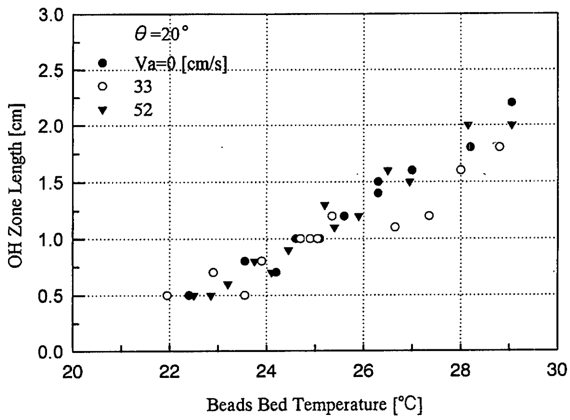

Figure 12 : Effect of Beads Bed Temperature on the Length of OH Luminescence Zone

length of OH zone increases clearly with increase in the beads temperature, namely increase in the thickness of the layered flammable gas mixture.

4. Concluding Remarks

Through the laboratory scale model experiment with the conditions ; the counter airflow less than 200cm/s, the ground surface inclination up to 20°, the ground temperature over the stoichiometric temperature of the combustion of spilled liquid fuel, the present study revealed some interesting and important results as follows;

(1) The OH zone propagates in the flammable gas layer of which the thickness is less than about 1cm. The thickness is nearly the same as that of the velocity boundary layer of the counter airflow.

(2) In the counter airflow, surface inclination has no large effect on the thickness of flammable gas layer on the ground.

(3) In the thin flammable gas layer, the images by OH luminescence zone and by the Schlieren photography have nearly the same shape at the flame tip.

(4) When the ground temperature is not so high, no flame propagation occurs in the counter flow of which the velocity is over the flame propagation velocity without the airflow.

(5) When the ground temperature is considerably higher than the stoichiometric temperature, however, horizontal flame propagation occurs even in the counter flow of which the velocity is over the flame propagation velocity without the airflow. This is due to the thickened layer of flammable gas mixture.

(6) Buoyancy has a large effect on the velocity of downward flame propagation along the inclined ground.

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