AERODYNAMIC STRUCTURE OF THE LEADING EDGE OF A DIFFUSION FLAME IN A BOUNDARY LAYER

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ABSTRACT

Characteristics of the aerodynamic and thermal structures near the leading edge of a stationary diffusion flame established in a boundary layer were examined by flow visualization and temperature measurements, and the effects of the reverse flow on the flame stabilization and the heat transfer mode were discussed. The aspects of the reverse flow region in front of the leading edge of the stationary flame were found to be similar to that of the spreading flame over a combustible material. A stagnation region was formed just ahead of the leading flame edge, and the gas stream passing through the flame zone was observed to be accelerated rapidly. The reverse flow was ascertained to scarcely affect on the heat transfer from the flame zone to the solid phase ahead of the leading flame edge. A stream in low velocity was observed to pass across the leading flame edge behind the stagnation region, and it was inferred that the reverse flow takes an important role in the stabilization of the flame. Although characteristics of a stationary diffusion flame were examined in this study, obtained knowledge could be adopted into the discussion on the spreading flame over combustible materials in windy conditions.

Keywords: Diffusion flame, boundary layer, aerodynamic and thermal structure, flame stabilization, mass and heat transfer, flow visualization.

INTRODUCTION

For the protection of fire hazards, knowledge of the flame spread mechanisms over combustible materials seems to be indispensable.[1,2] Most studies on the flame spread over the surface of a combustible material have been concerned with the phenomena in a quiescent atmosphere. However, many actual fires occur in windy conditions which must significantly affect the flame behavior.[3,4] Therefore, knowledge of the flame spread in an air stream is necessary for prevention of actual fire loss.

In our previous studies,[4-6] in order to explore the flame spread mechanisms over combustible porous solids, aerodynamic and thermal structures of the leading flame edge spreading over kerosene soaked sand in an opposed air stream were examined. In a wide range of the free stream velocities a stable reverse flow region in front of the leading flame edge was observed. It was inferred that the reverse flow provides a slow gas stream region necessary for the stability of a diffusion flame, through which gasified fuel molecules as well as heat from the reaction zone would be transferred in the upstream direction. This mass and heat transfer was assumed to be effective for increasing the flame spread rate or stabilizing the leading flame edge. Throughout these studies, characteristics of the leading flame edge were elucidated. However, in order to further clarify the flame spread mechanisms, it seems indispensable to explore the aerodynamic and thermal structures of the leading flame edge to a further extent.

In the present study, therefore, characteristics of the reverse flow region in front of the leading flame edge were examined in more detail using a stationary diffusion flame established in a boundary layer over a porous plate with fuel gas injection.

EXPERIMENTAL

A schematic diagram of the experimental apparatus is shown in Fig. 1. A tray of 60 cm long, 12 cm wide, and 2 cm deep was used. A settling chamber with a porous plate was set in the tray filled with wet sand. The porous plate made of sintered bronze was 10 cm x 10 cm surface area and 1 cm thick, the edge of which was located at 75 cm from the leading edge of the flat plate set up to be flush with the tray brim. The tray set in a temperature control bath was placed in the test section of a wind tunnel, where the air stream was uniform and its turbulence intensity was less than 1 %.

The diffusion flame was established by injecting fuel gas (propane) from the porous plate surface into an air stream flowing along the plate. The flow field was visualized with smoke streaks generated from a drip of $TiCl_4$ liquid. The behavior of the smoke streaks and the leading flame edge was examined on photographs taken with a motor-driven 35 mm camera or a high speed video camera. Local gas stream velocity was measured with suspended magnesium oxide particles and a repetitive illumination system. The velocity was obtained from the length of the interrupted trace of a particle on an enlarged photograph and the illumination interval. The temperature distribution near the leading flame edge was measured using a Pt/Pt-Rh thermocouple of wire diam. 0.1 mm.

RESULTS AND DISCUSSION

1. Aspects of Flow field

A stable diffusion flame was established under appropriate conditions of free stream velocity U and fuel injection velocity V_w. A blue leading flame edge followed by a luminous yellow zone was observed. As V_w increased or U decreased, the yellow zone became closer to the leading flame edge, and the distance between the flame zone and the porous plate. In order to examine the aspects of the flow field near the leading flame edge, the flow field close to the sand surface was visualized with smoke streaks generated from $TiCl_4$ liquid placed on upstream surface of the flat plate. Photographs of smoke streaks and leading flame edge for typical free stream velocities are shown in Fig. 2. These photographs clearly show the formation of a reverse flow in front of each leading flame edge. Characteristics of the aerodynamic structure near the leading flame edge were ascertained to be similar to those of the spreading flame over fuel soaked sand examined in our previous studies.[4-6] An example of the results obtained in a previous study[6] is shown in Fig. 3. Since the flow field of the stationary diffusion flame is similar to that of the spreading flame over the combustible material, the basic characteristics of the heat and mass transfer in these flames can be assumed to be almost the same.

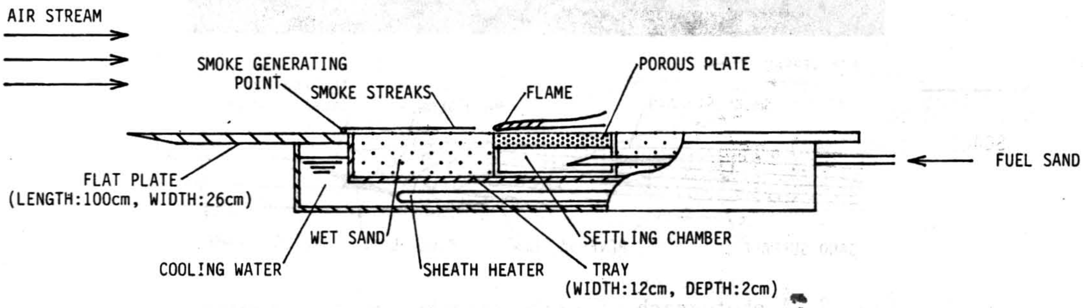

Fig. 1 Experimental apparatus.

2. Velocity Profiles near the Leading Flame Edge

A typical photograph of particle tracks which represent changes in local stream velocity passing the flame zone, and an illustration of the phenomena are shown in Fig. 4. Representative profiles of velocity component u in horizontal direction were shown. The outer boundary of the temperature increasing region was shown as an isotherm of 50℃. A stagnation region is found to be formed just ahead of the leading flame edge. On the upstream side of the stagnation region, a reverse flow occurs in the thin layer near the wall surface, while on the down stream side, the gas stream near the flame zone is accelerated rapidly. Overall aspects of the flow field in the present experiments are resemble with those observed in a previous experiment conducted on a stationary diffusion flame in two dimentional flow field

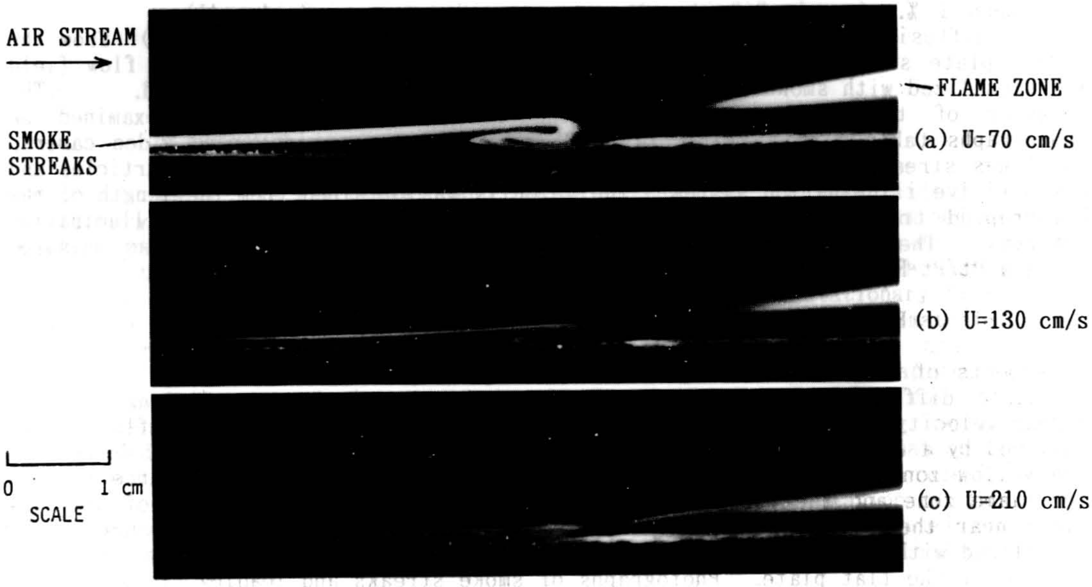

Fig. 2 Photographs of smoke streaks and the leading flame edge for typical free stream velocities. V_w=1.3 cm/s, exposure: 1/125 s.

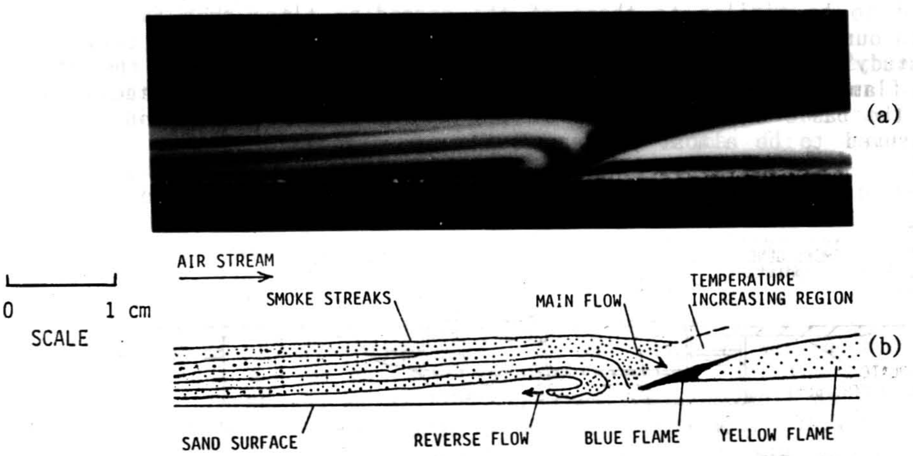

Fig. 3 A photograph of smoke streaks and the leading flame edge spreading over kerosene-soaked sand, and an illustration of the phenomena. Free stream velocity: 70 cm/s, initial sand temperature: 20 ℃, exposure: 1/125 s, smoke streaks: incense smoke.[6]

in a rectangular combustion chamber.[7] The formation of the reverse flow in the region close to the wall surface on the upstream side was recognized vividly in the present experiments conducted in an open space.

3. Temperature Distribution near the Leading Flame Edge

In order to understand the mechanisms of flame spread rate and flame stability in the air stream, knowledge of the thermal structure near the leading flame edge is important. Therefore, the temperature profiles across the boundary layers with flame were examined. Typical temperature profiles across the boundary layer are shown in Fig. 5. The temperature T increases with the distance y from the wall surface to a maximum at the flame zone. On the air stream side of the flame zone, T decreases with the increase y to the room temperature. T at the blue flame zone increases with the horizontal distance x from the edge of the porous plate. On the upstream side of the leading flame edge, where x is smaller than -0.1 cm, T decreases monotonously with the increase y. This fact indicates that heat is transferred from the sand surface to the surrounding gas phase and the heat transfer from the flame zone to the sand ahead of the leading edge caused mainly by the heat conduction through the sand layer. In the region where x is smaller than -0.3 cm, the heat transfer to this region by radiation or convection through gas phase is negligible, since T is small at the sand surface and decreases monotonously with the increase y.

Based on the temperature profiles shown in Fig. 5, temperature distributions near the leading flame edge were examined, and A typical result was shown in Fig. 6. In order to elucidate the relation between the temperature distribution and the flame zone, the shape of the blue flame zone was superimposed on the isotherms. The air stream side boundary of the flame zone is found to correspond to the isotherm of 800℃. From the temperature distribution ahead of the leading flame edge, it can be inferred that in the region of more than 0.3 cm from the leading

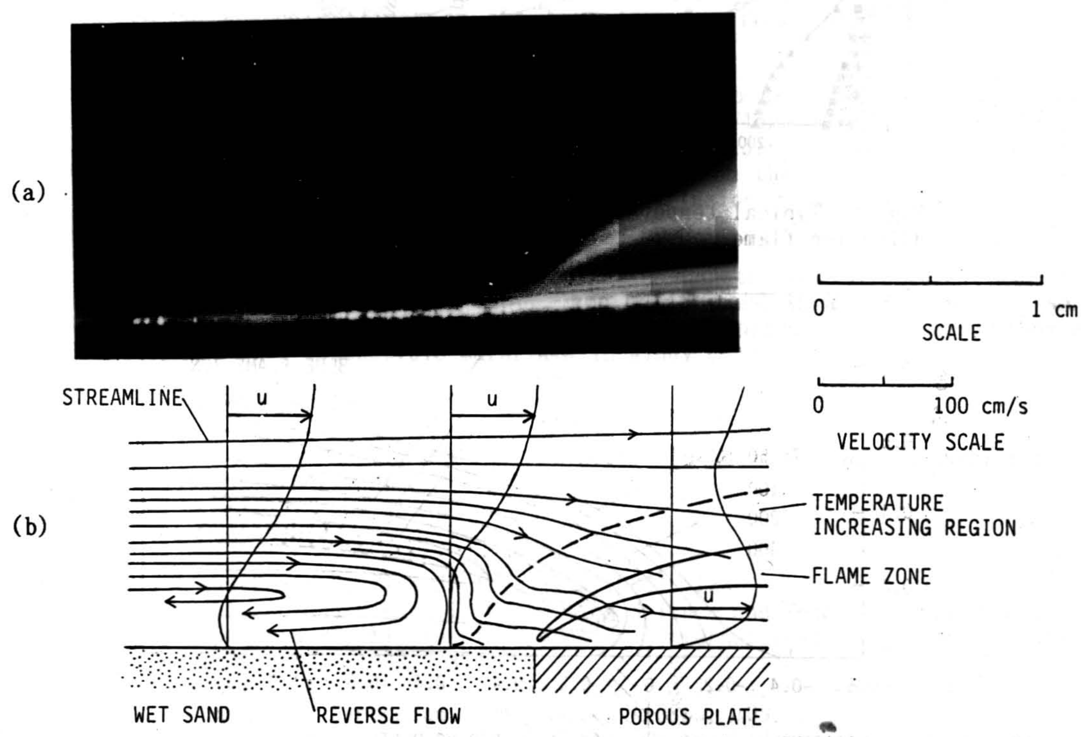

Fig. 4 A typical photograph of particle tracks and an illustration showing a flow field near the leading flame edge. U=70 cm/s, V_w=0.7 cm/s.

flame edge, the heat transfer from the gas phase to the solid phase does not occur. The gas phase temperature in the region of more than 0.5 cm from the leading flame edge is found to be close to the room temperature, even though the reverse flow near the surface is generated in a wide region in front of the leading flame edge. These facts imply that under the present experimental conditions the reverse flow scarcely affects the heat transfer from the flame zone to the solid phase ahead of the leading flame edge.

4. Characteristics of Reverse Flow

Based on the temperature distribution, it was ascertained that the reverse flow scarcely affects the heat transfer from the flame zone to the solid phase ahead of the leading flame edge, i.e., the main mode of the heat transfer must be conduction or convection near the leading flame edge. This results imply that the reverse flow has no appreciable effect on the flame spread rate in the case of the flame

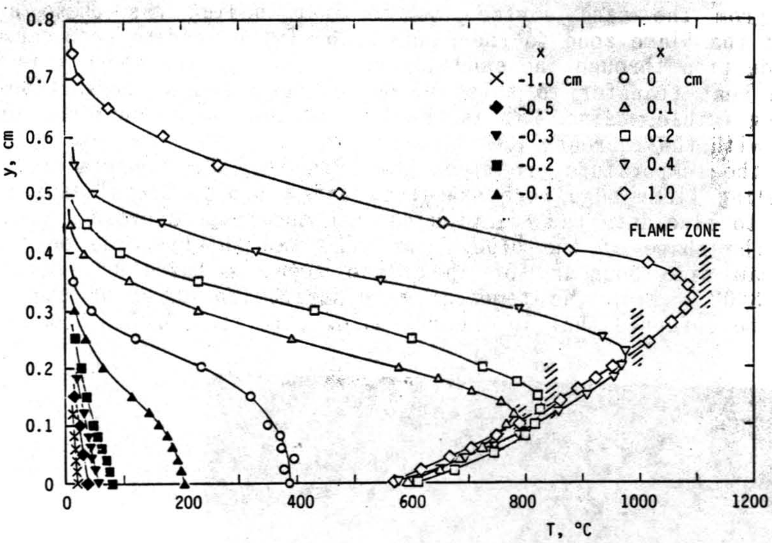

Fig. 5 Typical temperature profiles across boundary layers with diffusion flame. U=70 cm/s, V_w=0.7 cm/s.

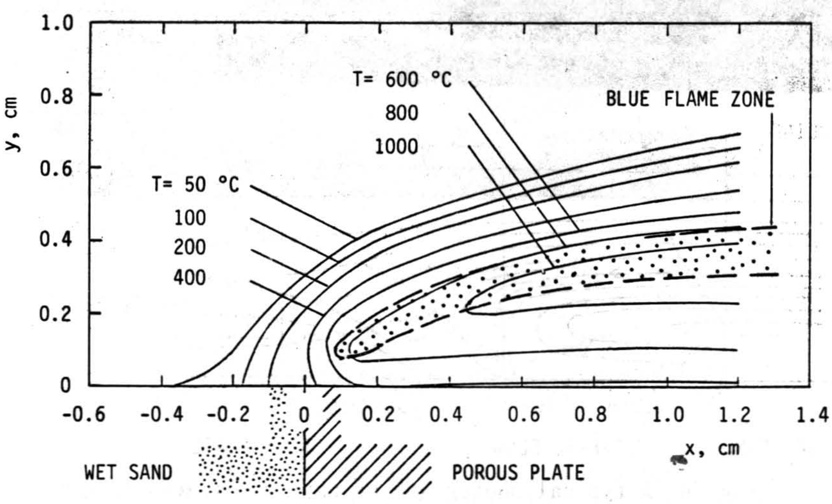

Fig. 6 Typical temperature distributions. U=70 cm/s, V_w=0.7 cm/s.

spread over combustible materials.

On the other hand, the formation of the stagnation region is found to provide a slow gas stream region between the stagnation region and the leading flame edge. A gas stream in low velocity was observed to pass across the leading flame edge behind the stagnation region as shown in Fig. 4. The stagnation region is considered to be formed closely connected with the reverse flow which can be observed in a wide range of the free stream velocities. Therefore, it is inferred that the reverse flow takes an important role in the stabilization of a diffusion flame established in the boundary layer even in an open space. For a discussion on the flame spread in an opposed air stream, it will be useful to explore the effects of the reverse flow on the flame stability to a further extent.

CONCLUSIONS

1. The aspects of the reverse flow region in front of the leading edge of a diffusion flame established in a boundary layer were examined by $TiCl_4$ smoke visualization technique. Since the flow field of the stationary diffusion flame is similar to that of the spreading flame over a combustible material, the basic characteristics of the heat and mass transfer in these flames can be assumed to be almost the same.

2. Changes in local stream velocity passing the flame zone were examined by a particle track technique. A stagnation region was found to be formed just ahead of the leading flame edge, and the gas stream passing through the flame zone was observed to be accelerated rapidly.

3. From the temperature distribution near the leading flame edge, the heat transfer from the flame zone to the solid surface ahead of the leading edge was found to be caused mainly by the heat conduction through the sand layer. The reverse flow was ascertained to scarcely affect on the heat transfer from the flame zone to the solid phase ahead of the leading flame edge.

4. The formation of the stagnation region was found to provides a slow gas stream region between the stagnation region and the leading flame edge, and a gas stream in low velocity was observed to pass across the leading flame edge behind the stagnation region. From these results, it was inferred that the reverse flow takes an important role in the stabilization of a diffusion flame established in the boundary layer even in an open space.

5. Although characteristics of the aerodynamic and thermal structures near the leading edge of a stationary diffusion flame established in a boundary layer were examined in this study, obtained knowledge could be adopted into the discussion on the flame spread over combustible materials in windy conditions.

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REFERENCES

1. Glassman I and Dryer F, Fire Safety J., 3(1980), 123.
2. Fernandez-Pello AC and Hirano T, Combustion Science and Technology, 32(1983), 1.
3. Suzuki T, and Hirano T, Nineteenth Symposium (International) on Combustion, The Combustion Institute, (1982), 877.
4. Suzuki T, Kawamata M and Hirano T, Fire Safety Science, Proceedings of the
5. Second International Symposium, Hemisphere, (1989), 199.
6. Suzuki T, Kawamata M, Matsumoto K and Hirano T, Proceedings of the ASME/JSME Thermal Engineering Joint Conference 1991, ASME, (1991), 341.
7. Hirano T and Kanno Y, Fourteenth Symposium (International) on Combustion, The Combustion Institute, (1973), 391.