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Diffusion Flame Stabilized on a Porous Plate in a Parallel Airstream

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Effects of an obstacle on the structure and stability of a laminar diffusion flame established on a porous plate in a parallel airstream have been investigated experimentally. The obstacle, a backward-facing step or a rectangular cylinder, is located upstream of the porous plate through which gaseous methane is injected uniformly. Structures of the flame are elucidated by the direct and schlieren photography. Flame shapes are described and stability diagrams are plotted for the freestream velocity and the fuel injection velocity, which are discussed with flow structures.

I. Introduction

STUDIES of the structure and the stability of various types of diffusion flames have been performed by many researchers. Counterflow diffusion flames, which can be regarded as a one-dimensional flame on a stagnation streamline, have been surveyed by Tsuji,[1] from which the structures of diffusion flame have been elucidated and the global reaction rate of fuel/oxidant has been estimated. One of the fundamental types of diffusion flames is that of diffusion flame established in a boundary layer on a flat plate that has a two-dimensional character. After Emmons[2] developed the similarity solution to this problem, Hirano and Kanno[3] and Hirano and Kinoshita[4] performed experiments on the diffusion flames over a plate made of porous metal through which a fuel gas was injected and over a liquid fuel surface. They observed that velocity overshoot occurred near the flame zone, which could not be predicted by Emmons's theory. This phenomenon was also pointed out by Johns et al.[5] in a turbulent boundary layer. Lavid and Berlad[6] analyzed this phenomenon by the perturbation method using a small parameter that was proportional to the buoyancy effect. Ohyagi et al.[7] showed experimentally that Emmons's solution could predict a burning rate expression of a methanol surface as a function of Reynolds number based on a freestream velocity provided that effects of gravity dominated the flow structure. Regarding the velocity overshoot mechanism, Wang et al.,[8] using a numerical computation, concluded that the velocity overshoot may be caused by the effects of thermal expansion and the baroclinic torque. Concerning the extinction and stability process, Ramachandra and Raghunandan[9] clarified that it was believed to be due to the thermal quenching of the flame, and they also investigated the influence of buoyancy.[10] Mao et al.[11] performed a numerical analysis of a diffusion flame stabilized over a solid fuel, which solved the flame structure for both forced and buoyancy-induced flows. Frey and Ti'en[12] also numerically simulated a phenomenon of flame spread over a solid fuel, which is closely related to the boundary-layer combustion.

From a practical point of view, the stabilization of diffusion flame is still a crucial problem because in industries many practical burners or furnaces use the diffusion flame rather than a premixed flame for the sake of safety. In the premixed system, the problem of flame stabilization behind an obstacle as a flame holder is one of the most fundamental problems and has been studied extensively for practical purposes.[13] On the other hand, for nonpremixed flames flowfields in which the diffusion flames are stabilized seem to be simple. In most cases, the flame is stabilized near the point where a fuel gas and oxidant gas collide with each other so that there seems to be no critical problem. However, for the flame established in the flat plate boundary-layer flow, wall heat loss and catalytic reactions affect the stability and the structure of the leading edge of the flame.[14] In particular, the stability of the flame depends on the detailed flow structure near a leading edge of the burners. Ohyagi et al.[15] conducted an experimental study of the flame stabilization using a cylinder situated with its axis perpendicular to the main stream at the upstream side of the front edge of the liquid fuel surface. The results show that, in certain conditions of the freestream velocity and the distance between the cylinder and the edge, the flame can be stabilized on the cylinder. Raghunandan and Yogesh[16] put a thin diaphragm as an obstacle at the leading edge of a porous plate to study its effects on the stability, structure, and heat transfer to the wall. These two experimental studies reported that a recirculating flow established behind the obstacle played an important role in affecting the structure and the stability of flame. However, due to the complexity of the flow behind the obstacle, the behaviors of the flame have not been clarified completely.

In the present study, an experiment was performed on the diffusion flames established behind two types of obstacle, i.e., a backward-facing step and a rectangular cylinder that was situated upstream of a porous plate through which a fuel gas was injected. The flames were observed and the flowfields were visualized by both direct photography and schlieren photography from which stability limits were plotted on the diagram of the freestream velocity vs the fuel injection velocity. The objective of this experimental study was to examine in detail the stability mechanism of diffusion flame for various types of obstacle and for various flow conditions. Of course, the results will not be applied directly to the design of a practical burner or a furnace, but they might be utilized to understand the mechanisms of the stabilization of diffusion flames on various types of burner.

II. Experiment

The experiment was performed in a test section with its cross section 30×250 mm and length 300 mm connected to an outlet of a low-speed wind tunnel that was mounted horizontally in the laboratory. Figure 1 shows a schematic of the experimental apparatus. The inside walls of the section were equipped with windows of Vicor glass. The fuel gas used was methane (98% pure), and it was fed through a porous metal plate (a sintered bronze with porosity of 2 μm) embedded flush in a bottom surface of the section. The distance from the inlet of the chamber to the leading edge of

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Table 1 Experimental conditions

Element	Characteristic
Test section	Height 250 mm Width 30 mm Length 300 mm
Burner plate	Sintered bronze (porosity 2 μm), length 70 mm, width 19 mm
Fuel	Methane (purity 98%)
Fuel injection velocity v_w	0.001–0.1 m/s
Oxidizer	Air
Freestream velocity U_∞	0.3–3.0 m/s

Table 2 Experimental conditions: type of obstacle

Case	Obstacle	Height H	Distance D
1	No	——	——
2	Step	5	10
3	Step	15	10
4	Step	10	10
5	Step	10	40
6	Rectangular cylinder	5	10
7	Rectangular cylinder	10	10
8	Rectangular cylinder	10	30

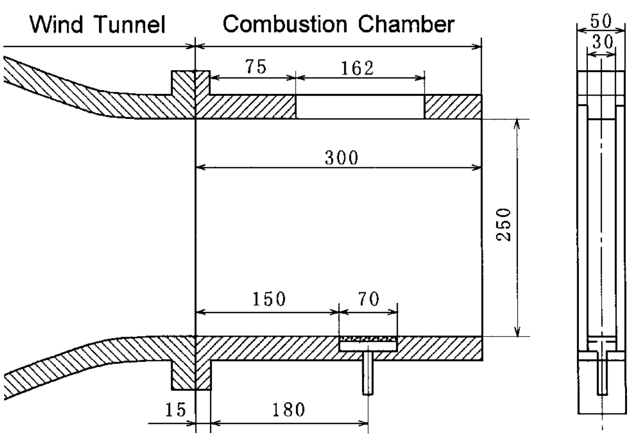

Fig. 1 Schematic of experimental apparatus.

the porous plate burner was fixed to 15 cm, and the length of the porous plate burner was 7 cm. In a ceiling of the section, a slit of 5 × 131 mm for inserting probes was equipped. Volumetric flow rates of the air and the fuel were metered by orifices. Freestream velocity of air was defined as a volumetric flow rate divided by the area of the cross section of the chamber. The x axis is in the streamwise direction with its origin at the leading edge of the porous plate, and the y axis is perpendicular to the burner surface measured from it. As an obstacle, a backward-facing step or a rectangular cylinder placed on the wall upstream of the burner plate was used. Both of obstacles had 30 mm in width fitted the width of test section. The backward-facing step had a sufficient length to stabilize the velocity profile on it. Heights of the step and the rectangular cylinder H were varied as a parameter from 5 to 15 mm. The rectangular cylinder was placed on the wall perpendicular to the flow direction, and its cross section was $H \times 10$ mm^2. A distance D from a backward face of these obstacles to the leading edge of the porous burner was also varied from 10 to 40 mm. The freestream velocity U_∞ and the fuel injection v_w were varied from 0.3 to 3.0 m/s and 0.001 to 0.1 m/s, respectively. These experimental conditions are summarized in Tables 1 and 2.

Observation of flame was performed by both direct and schlieren photography. Direct photographs were taken by using a still camera with color films (ISO 1600) at $\frac{1}{30}$- to $\frac{1}{60}$-s shutter speed. The schlieren system as shown in Fig. 2 was organized using two concave mirrors (200 mm in diameter) and one Xe flash lamp (2 μs in duration) as a light source. The schlieren photographs were taken with a tricolor filter (red, green, blue) of which the color borders were horizontal as well as vertical to the porous plate. The incidence light was focused on the border between the red and green regions.

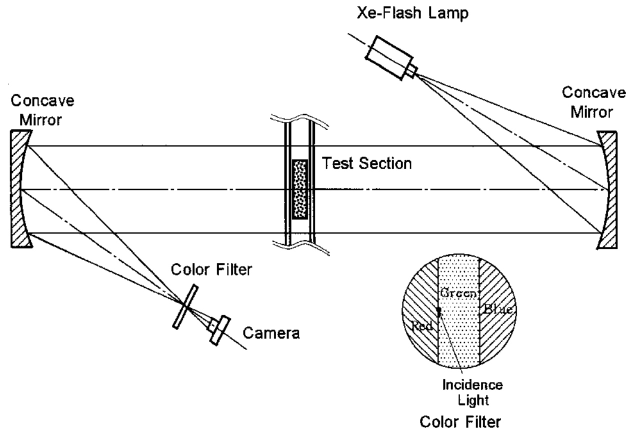

Fig. 2 Schlieren system.

Flame stability limits were obtained for the conditions listed in Tables 1 and 2 by observing the flame shapes.

III. Results and Discussion

A. Types and Structures of Flames

Before discussing stability limits of the flame, the types and the structures of flame are described here. In the present study, observed flames may be classified into five main types: 1) plate-stabilized flame, 2) lifted flame, 3) obstacle-stabilized flame, 4) separated flame, and 5) oscillating flame.

A plate-stabilized flame as shown in Fig. 3a is a flame whose leading edge (LEF) contacts the front edge of the burner wall (strictly speaking, the LEF separates from the wall within 1 mm caused by a quenching effect). Here the freestream velocities U_∞ and the fuel injection velocities v_w are 1.0 and 0.07 m/s, respectively. In this experimental condition, the LEF ($x = 0$ to about 10 mm) is blue, and it turns to bright yellow downstream due to soot formation. The flame shape is essentially two dimensional. When U_∞ and v_w are very small, however, the flame oscillates vertically due to the buoyancy effect downstream. Decreasing v_w causes the blue flame region to become larger. Corresponding to the direct one, a schlieren photograph of this flame is shown in Fig. 3b. Color boundaries in the color filter are horizontal and vertical for the left and right photographs, respectively. In diffusion flames, density distributions are complex compared with those in premixed flames. As the density gradient across the diffusion flame is small (zero at the flame center), the flame position cannot be distinguished clearly unless it is compared with the direct photographs. Because pressure does not change considerably in this field, a density distribution is mainly determined by those of temperature and concentration of chemical species. In the horizontally set up schlieren image (left), there are three red zones corresponding to a large density gradient. The outer red zone on the air side corresponds to a zone where the temperature decreases from the flame temperature to the ambient temperature. In this zone, there appears a thin dark line near the leading edge of the thermal boundary layer where the temperature gradient is very steep. The middle red zone corresponds to a region where the temperature decreases, i.e., the density increases, toward the wall. In the inner red zone near the wall, while the temperature decreases toward the wall, the concentration of the injected fuel (methane) should be increased so that the density will decrease. After all, there are two extrema of density in the vertical direction. One is at a yellow zone between the outer and middle red zone where the flame should exist as estimated from the direct photograph. The other is at a yellow and partly faint blue zone below which the density decreases due to the fuel injected. From the photograph of the vertically set up color border (right), it is evident that the density gradient in the streamwise direction is very small except at the leading edge of the burner where the flame is stabilized.

A lifted flame (see Fig. 4a for the case with the step where $D = 10$ mm, $H = 10$ mm, $U_\infty = 2.5$ m/s, and $v_w = 0.04$ m/s) is a flame with the flame edge lifting up from the burner but not attaching to the obstacle. Strictly speaking, this type of flame is defined as that of the LEF separated from both the burner wall and the face of the obstacle by more than 2 mm. Thus the LEF remains in the recirculating zone behind the step. The flame does not show a significant oscillation, and the whole of the flame shows a quasi-two-dimensional feature. For the case with the rectangular cylinder, this type of flame is rarely observed due to the complexity of the flow, and it is appropriate to classified it as a separated flame to be defined later. The color schlieren photograph corresponding to Fig. 4a is shown in Fig. 4b. Similar to the plate-stabilized flame three red regions are easily confirmed. Also, there is a recirculation zone with a density gradient near the backface of the step, where the flame does not exist. In this flame, the flowfield is still laminar.

An obstacle-stabilized flame is defined as a flame with the LEF attached to the backward face of the obstacle. Corresponding to which obstacle is used, in a later subsection this type is distinguished as a step-stabilized flame (see Fig. 5a, where $D = 10$ mm, $H = 10$ mm, $U_\infty = 3.0$ m/s, and $v_w = 0.1$ m/s) and a rectangular cylinder-stabilized flame (see Fig. 5b, where $D = 0$ mm, $H = 10$ mm, $U_\infty = 1.0$ m/s, and $v_w = 0.05$ m/s). This type of flame can be obtained by increasing U_∞ or decreasing D from the plate-stabilized flame or lifted flame. For the case with the backward-facing step, this type of flame is very stable in the whole of the flame. In all conditions, vertical and horizontal oscillations of the flame are seldom observed. For the case with the rectangular cylinder the LEF is stabilized just at the rear top corner of the cylinder. In this case, after a limited stable region the flame oscillates in the vertical direction considerably. As a result the flame shows an unsteady, complex three-dimensional structure, and the luminous zone of the flame seems to be very thick for an exposure time of $\frac{1}{30}$ s. The direct photograph for the case with the rectangular cylinder is shown in Fig. 5b, and the schlieren photograph is shown in Fig. 5c. A density variation appears from the front corner of the cylinder, whereas the flame tip lingers at the rear top corner as a thin black line in the reddish zone. As the flow separates at the front corner, hot gaseous products from the flame are entrained to the front corner, whereas the fuel gas resides behind the cylinder so that the flame is stabilized at the rear corner. In this case, in particular for the image obtained by the vertical color borders, vortices shedded from the cylinder are clearly seen. These are the von Kármán vortices modified by the existence of the wall, and the shedding rate is about 14.5 Hz. The thick luminous zone observed by the direct photograph is a result of this oscillation.

A separated flame is defined as a flame in which the LEF separates from the obstacle and/or the burner wall and is observed for the cases with no obstacle and rectangular cylinder. It is distinguished from the lifted flame because this type of flame is very unsteady and shows a complex three-dimensional shape in its structure, whereas the other types are mostly two dimensional and steady. For the case with no obstacle, as increasing U_∞ from a plate-stabilized flame, a V-shaped flame is observed in which a central part of the LEF separates from the burner edge (symmetric separated flame) as shown in Fig. 6. If the velocity U_∞ is increased more, the flame separates from one of the corner edges (asymmetric separated flame) as shown in Fig. 7. These phenomena will be discussed in detail in the next subsection. If U_∞ is increased more, the flame is completely separated from the edge and blows out from the combustion chamber itself. For the case with the rectangular cylinder, the same phenomena are observed, but in this case the flame is affected by the complex flow structure of recirculation and vortices (Fig. 8). For the case with the step, this separated flame cannot be observed within the velocity range of the present experiment. If it were possible to increase the main velocity U_∞, the separated flame might be observed for this case.

An oscillating flame is observed for low fuel injection velocity regions and has a remarkable periodic oscillation of the LEF in the horizontal direction over 2 mm in amplitude and is almost blue in color. As a result of a further decrease of the fuel injection velocity, the flame is extinguished due to the heat loss to the burner plate.

B. Flame Stability Diagrams

To illustrate on which conditions those flames described by the preceding subsection appear, we plotted flame stability diagrams in a plane of the freestream air velocity U_∞ and the fuel injection velocity v_w for each case with and without the obstacles.

1. *No Obstacle*

Figure 9 shows a flame stability diagram for no obstacle. In this case, plate-stabilized, separated, and oscillating flames are observed in the present experimental conditions. The plate-stabilized flame can be obtained when v_w is larger than 0.8 cm/s, and U_∞ is smaller than 1.1 m/s. Under these conditions, the fuel and the oxidant are mixed well at the front edge of the burner to provide a combustible gas that is consumed by the LEF. To keep the flame as a plate-stabilized flame, it is necessary to increase the chemical reaction rate as U_∞ becomes larger, that is, to increase the amount of fuel. Meanwhile, when v_w is more than 3 cm/s, increasing U_∞ gradually forms a symmetric separated flame. When U_∞ is increased more than 1.6 m/s, the LEF separates from the burner asymmetrically. These phenomena are attributed to the effects of boundary layers on the side wall. In the corner regions where the two boundary layers intersect each other, low-speed regions exist above the quenching distance from the burner plate in which the chemical reaction can start. An angle of the V-shaped flame front is determined by U_∞ and the burning velocity of a mixture created in front of the flame.

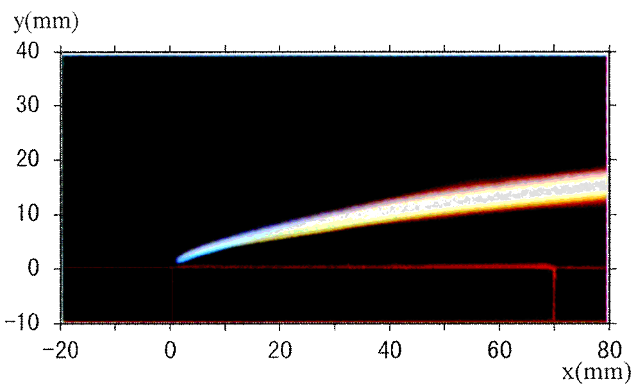

Fig. 3a Direct photograph of plate-stabilized flame (no obstacle, U_∞ = 1.0 m/s and v_w = 0.07 m/s).

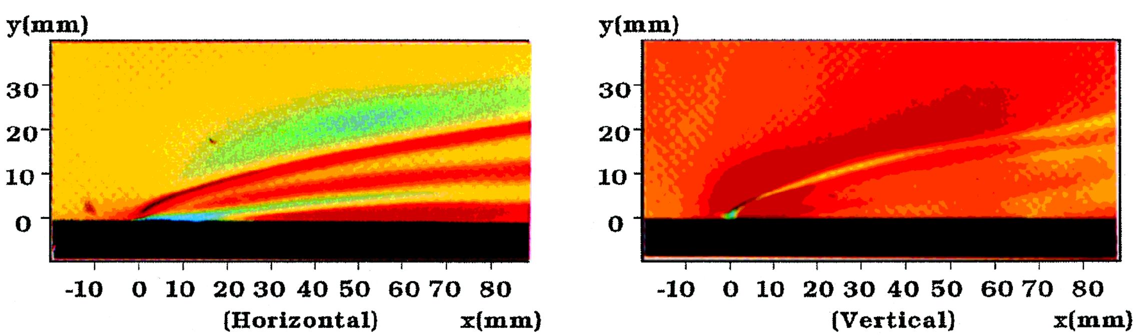

Fig. 3b Color schlieren photographs of plate-stabilized flame (no obstacle, U_∞ = 1.0 m/s and v_w = 0.07 m/s).

As U_∞ is increased, the flame separates from one of the corners to become an asymmetric separated flame. Increasing U_∞ further causes the flame to be a blow out if v_w is large enough to form a rich mixture on the burner surface. For v_w less than 3 cm/s and more than 3 mm/s, an oscillating flame region appears above the region where the flame is extinguished. In the oscillating region, a fuel supply is so small that a mixture in front of the burner edge is not combustible. Then the flame is blown off from the edge; however, it creates a fresh mixture in front of it through which a flame propagates upstream. In this cycle, the flame oscillates horizontally. If v_w is decreased further, the mixture created should be out of the flammability limit and the flame should be extinguished. Figure 10 shows a result of an experiment to observe the effects of dilution of fuel. The fuel (methane) was diluted by nitrogen before it was introduced to the burner plate. This is the case without an obstacle and $U_\infty = 1.0$ m/s. The figure shows a stability diagram with v_w and the fuel volume fraction $\chi = [CH_4]/([CH_4] + [N_2])$. Note that an oscillating flame was also found between the plate-stabilized flame and the extinction regions as in Fig. 9.

2. *Backward-Facing Step*

For the case with the backward-facing step, the stability diagrams are shown in Fig. 11a for case 2 ($H = 5$ mm and $D = 10$ mm), Fig. 11b for case 3 ($H = 15$ mm and $D = 10$ mm), Fig. 11c for case 4 ($H = 10$ mm and $D = 10$ mm), and Fig. 11d for case 5 ($H = 10$ mm and $D = 40$ mm).

In the present velocity range, as shown in Fig. 11a, using the step as an obstacle eliminates the separated flame and the blow out regions that are observed in the case of no obstacle. Instead of these regions, lifted and step-stabilized flames appear. The existence of the step has important effects on holding and stabilizing the flame through establishing a recirculating flow behind it. The oscillating flame region is reduced significantly because the step provides a combustible mixture around the LEF independent of the velocity U_∞. Plate-stabilized flames appear in the region where U_∞ is less than 1.0 m/s and v_w is larger than 0.5 cm/s; however, the limiting line inclines with a negative slope that is the reverse of the case of no obstacle. This phenomenon can be interpreted as follows: as v_w is increased, the quantity of the fuel convected upstream becomes greater and the LEF is shifted up to form lifted flames. From the lifted flame condition, increasing U_∞ intensifies the recirculating flow. Therefore the fuel is more transported upstream to make the LEF closer to the step face, and finally the step-stabilized flame is established.

Comparing Fig. 11a with Fig. 11b, one can confirm the effects of increasing step height H on the improvement of the stable regions. In case 2 where $H = 5$ mm, a limiting line between the extinction and the oscillating flame regions does not show a substantial difference from that of case 1. But in case 3 where $H = 15$ mm, this line becomes lower so that a flame-existing area is enlarged, and it is remarkable that the region of the step-stabilized flame expands greatly. On the other hand, the region of the plate-stabilized flame does not change significantly. These facts can be interpreted as follows: Behind the step a recirculation zone is created whose size is dependent on the height. As the height H becomes larger, the recirculating vortex should become larger too. Therefore, the step-stabilized flame can be obtained even for small U_∞ and small v_w. The mixture created on the burner surface should be richer than that in small recirculation so that the extinction occurs at a smaller fuel supply.

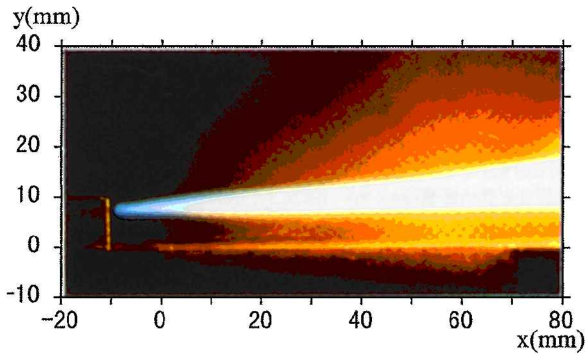

Fig. 5a Direct photograph of step-stabilized flame ($D = 10$ mm, $H = 10$ mm, $U_\infty = 3.0$ m/s, and $v_w = 0.1$ m/s).

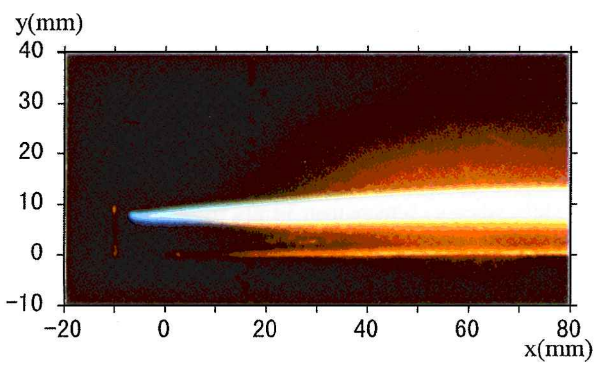

Fig. 4a Direct photograph of lifted flame (step, $D = 10$ mm, $H = 10$ mm, $U_\infty = 2.5$ m/s, and $v_w = 0.04$ m/s).

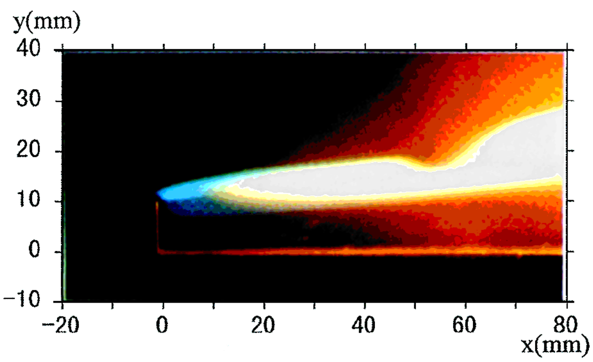

Fig. 5b Direct photograph of rectangular cylinder-stabilized flame (rectangular cylinder, $D = 0$ mm, $H = 10$ mm, $U_\infty = 1.0$ m/s, and $v_w = 0.05$ m/s).

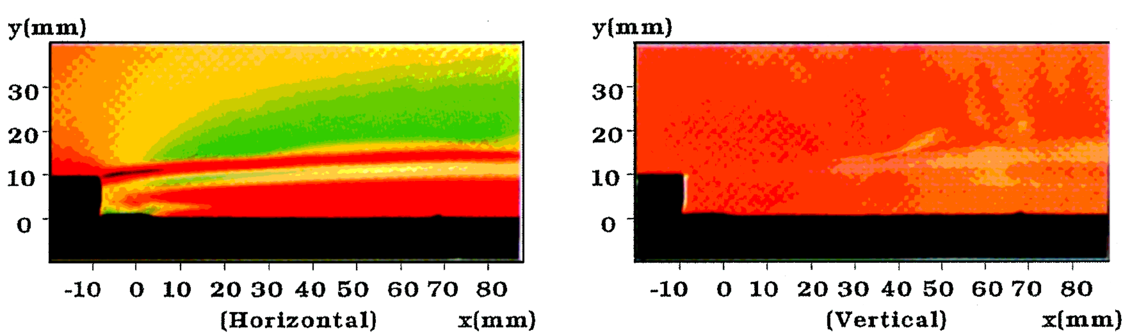

Fig. 4b Color schlieren photographs of lifted flame (step, $D = 10$ mm, $H = 10$ mm, $U_\infty = 2.5$ m/s, and $v_w = 0.04$ m/s).

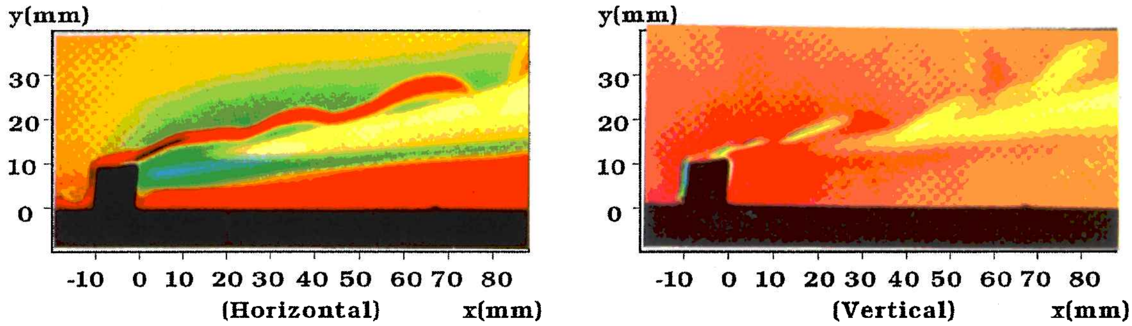

Fig. 5c Color schlieren photographs of rectangular cylinder-stabilized flame (rectangular cylinder, $D = 0$ mm, $H = 10$ mm, $U_\infty = 1.0$ m/s, and $v_w = 0.05$ m/s).

Fig. 6 Bird's eye view of symmetric separated flame for no obstacle ($U_\infty = 1.5$ m/s and $v_w = 0.07$ m/s).

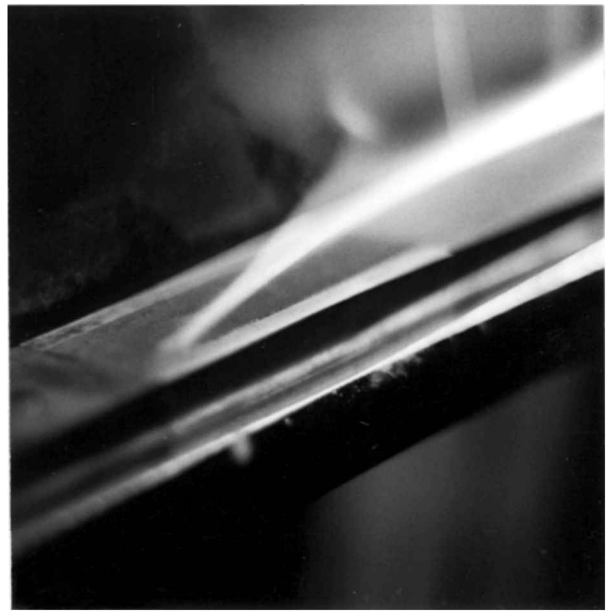

Fig. 7 Bird's eye view of asymmetric separated flame for no obstacle ($U_\infty = 2.0$ m/s and $v_w = 0.07$ m/s).

The explanation mentioned earlier can be also applied for the effect of D shown in Fig. 11c (case 4 where $H = 10$ mm and $D = 10$ mm) and Fig. 11d (case 5 where $H = 10$ mm and $D = 40$ mm). It is clear that as a result of increasing D the step-stabilized flame region becomes smaller, and at a certain distance D (between 10–20 mm for $H = 10$ mm) it disappears due to the insufficiency of the recirculating flow intensity to transport fuel upstream within the present experimental condition. This phenomenon is followed by conspicuous expansion of both the plate-stabilized and oscillating flame regions.

Before these experiments were done, a flow visualization with the particle track method was performed for nonreacting flows using TiO_2 particles for airflow and smoke of a joss stick for fuel flow. From these visualization experiments, an estimate of the flow condition with the ratio D/H may be considered as follows. For small D/H, the front edge of the burner plate is considered to be located inside the recirculation zone for no injection; then, if the gas is injected from the porous burner, it will be entrained by the recirculating vortex that mixes the air and fuel. In this case, a step-stabilized flame is easily formed, and the area of this flame in the stability diagrams increases as D/H decreases as shown in Figs. 11a–11d, which correspond to $D/H = 2$, $\frac{2}{3}$, 1, and 4, respectively. On the other hand, for large D/H, the recirculating vortex is occupied only by the air, and the mixing region could not approach the step. Therefore, plate-stabilized flame and lifted flame will be established easily instead of step-stabilized flame.

3. *Rectangular Cylinder*

In the case with the rectangular cylinder, several types of flames that have complex structures are observed. Flame stability diagrams are shown in Fig. 12a for case 6 ($H = 5$ mm and $D = 10$ mm), Fig. 12b for case 7 ($H = 10$ mm and $D = 10$ mm), and Fig. 12c for case 8 ($H = 10$ mm and $D = 30$ mm). Note that in these cases most of the flames are unsteady and cannot be considered as stable flames. In case 6, due to the complexity of the flow there is no flame that could be classified as plate-stabilized flames. Lifted flames are observed only for U_∞ less than 1.6 m/s, and these flames show three-dimensional structures affected by interactions between vortices produced behind the rectangular cylinder and the side walls. For U_∞ more than 1.7 m/s, separated flames are observed as they are observed in the case without obstacle. In this region increasing v_w makes one side of the LEF separate, whereas increasing U_∞ results in blow out of the flame. The mechanisms of these phenomena are considered similar with the case of no obstacle.

In case 7, when increasing H from 5 to 10 mm, that is, when decreasing D/H from 2 to 1, rectangular cylinder-stabilized flames are observed as was expected; however, plate-stabilized flames are observed in spite of smaller D/H. In contrast to the flow behind the step, the flow behind the cylinder is unsteady so that a flow in the downstream region is much more influenced by the vortical flow and the complexity rises as the height H is larger. Therefore, the border line between lifted flames and separated flames is hard to distinguished. Consequently, it is not plotted here. Increasing U_∞ from rectangular cylinder-stabilized flames separates the LEF from the face of rectangular cylinder to form separated flames. In this insecure region, increasing the fuel injected velocity v_w causes the flame to blow out. This fact probably corresponds to the instability of the recirculating flow caused by larger v_w, which influences transportations of a combustible gas to the LEF.

If D/H is increased to 3 as in Fig. 12c, the flames almost exist in the region of separated flames. For high v_w the flame approaches the cylinder and is stabilized as U_∞ is increased. But note that the LEF

Fig. 8 Bird's eye view of separated flame for rectangular cylinder (D = 10 mm, H = 10 mm, U_∞ = 1.5 m/s, and v_w = 0.07 m/s).

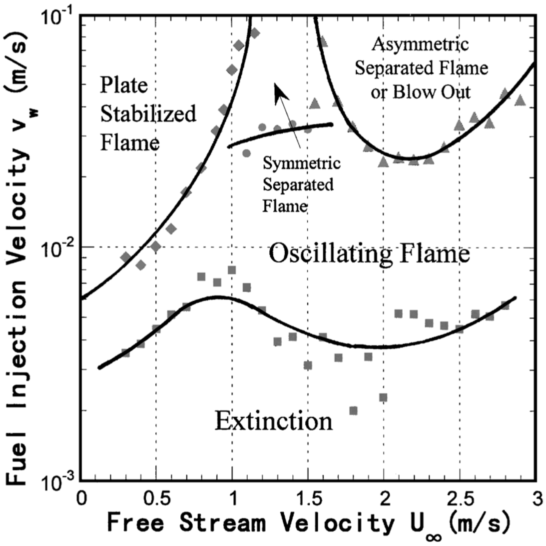

Fig. 9 Stability diagram for case 1 (no obstacle).

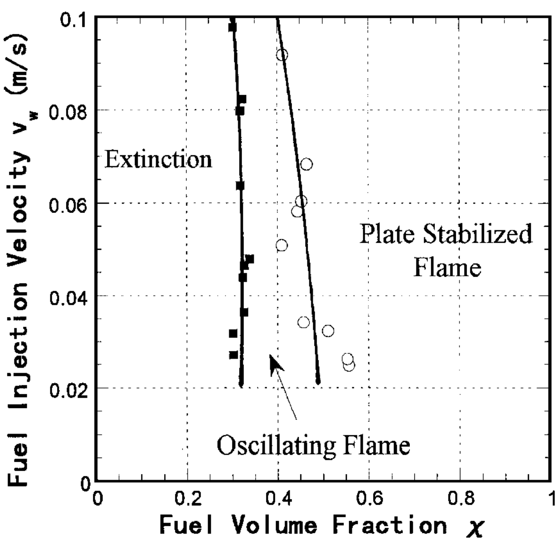

Fig. 10 Stability diagram for dilution of fuel (no obstacle, U_∞ = 1.0 m/s).

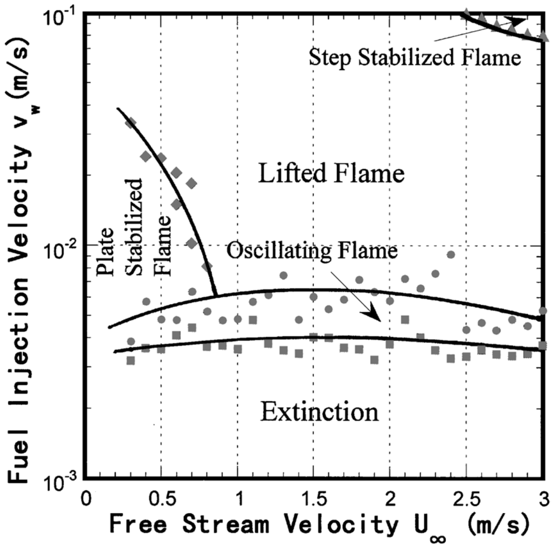

Fig. 11a Stability diagram for step for case 2 (H = 5 mm and D = 10 mm).

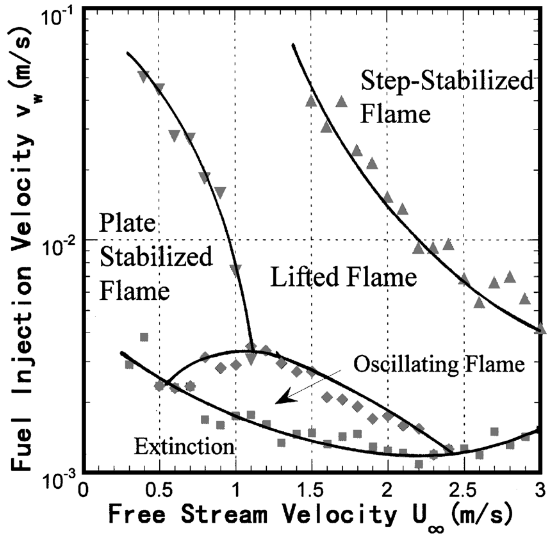

Fig. 11b Stability diagram for step for case 3 (H = 15 mm and D = 10 mm).

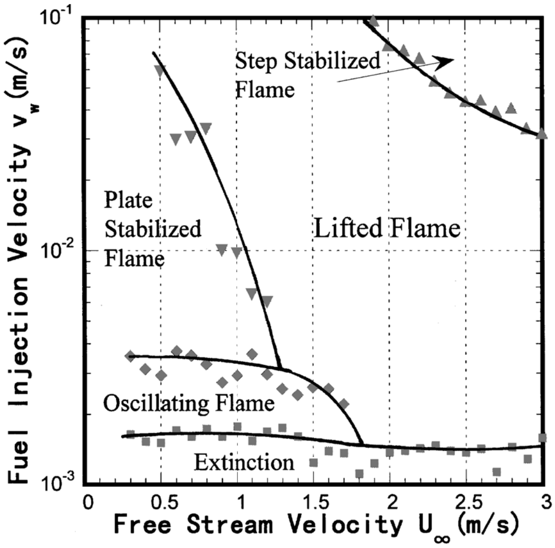

Fig. 11c Stability diagram for step for case 4 (H = 10 mm and D = 10 mm).

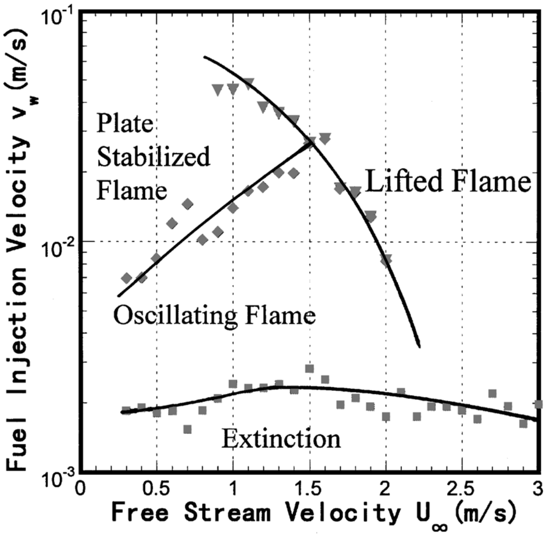

Fig. 11d Stability diagram for step for case 5 ($H = 10$ mm and $D = 40$ mm).

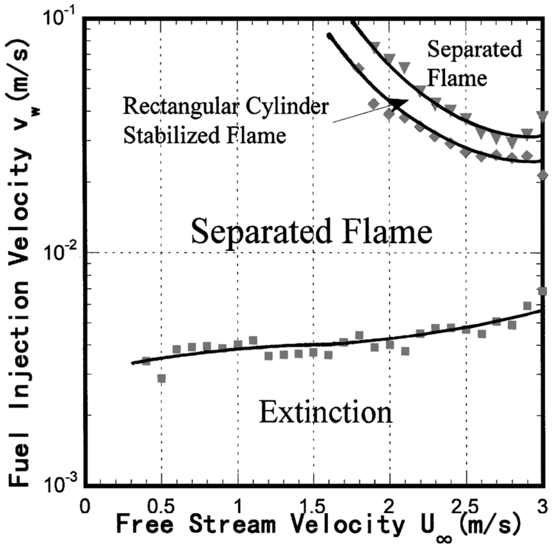

Fig. 12c Stability diagram for rectangular cylinder for case 8 ($H = 10$ mm and $D = 30$ mm).

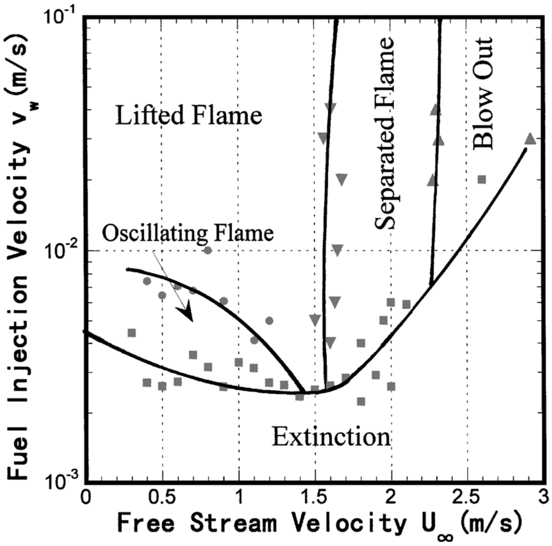

Fig. 12a Stability diagram for rectangular cylinder for case 6 ($H = 5$ mm and $D = 10$ mm).

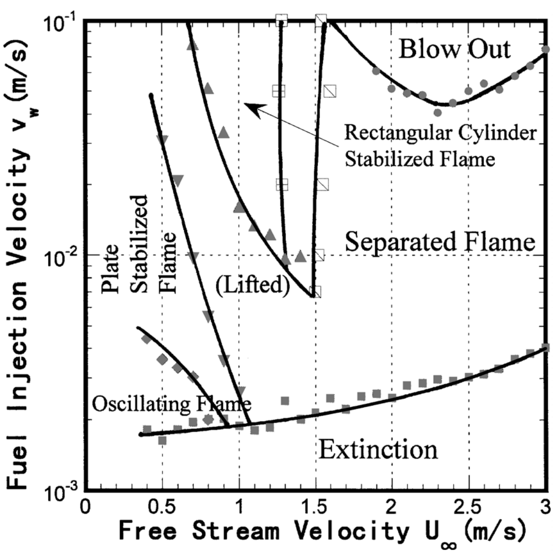

Fig. 12b Stability diagram for rectangular cylinder for case 7 ($H = 10$ mm and $D = 10$ mm).

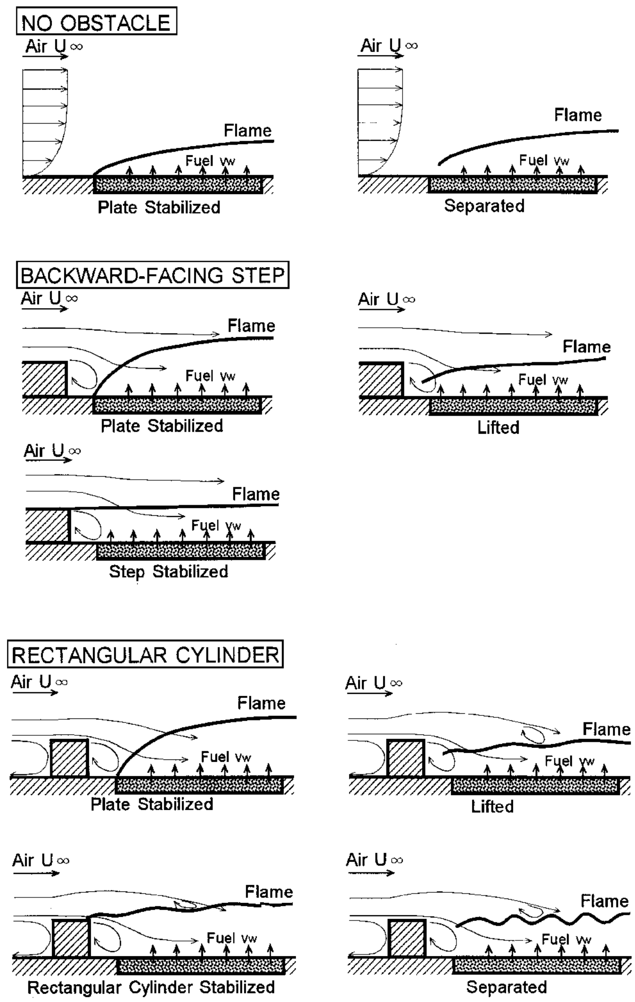

Fig. 13 Schematics of stable flames observed.

separates again as soon as the v_w or U_∞ is increased. Rectangular cylinder-stabilized flames appear in a very restricted region where the mixture ratio at the rear top corner should be near stoichiometric. Concerning this phenomenon, it should be emphasized that in the case with the rectangular cylinder the flowfield is very complex and unsteady so that the flame's stability cannot be defined in a strict sense. Also, the mechanism of flame stabilization behind the rectangular cylinder cannot be explained as clearly as that of the flame behind the backward-facing step.

Figure 13 shows the schematics of the stable flames observed in the present experiment. For the case of the step, three types of flame are observed, i.e., plate-stabilized flame, step-stabilized flame, and lifted flame. Both increasing height H and decreasing distance D or decreasing D/H extend the magnitude of the recirculating flow, and consequently the stable flame regions spread out. For the case of the rectangular cylinder, even though plate-stabilized flame and rectangular cylinder-stabilized flame are observed at relative low freestream velocity, the types of flame are generally unsteady and more complicated due to complex unsteady flow established behind the rectangular cylinder.

IV. Conclusion

The experimental investigation of the laminar diffusion flame over a porous plate burner and of the influence of an obstacle (a backward-facing step and a rectangular cylinder) has been discussed. Flame structures of some typical flames are elucidated by the direct and schlieren photographs. The flame shapes and their stability limits are discussed with the stability diagrams. For the case without an obstacle, the flame in a two-dimensional boundary layer is observed and the stability is essentially determined by the formation of a combustible mixture at the front edge of the burner. In contrast with this case, the presence of a backward-facing step or a rectangular cylinder has considerable effects on the stability of the flame by producing a recirculating flow. For the case of no obstacle there is no stable flame existing in the region $U_\infty > 1.2$ m/s and $v_w < 0.1$ m/s, whereas for the case of the step the flame is stabilized by the step even if U_∞ is increased to 3.0 m/s. It is clear that the regions of stable flame in the stability diagrams are considerably enlarged by the existence of the obstacle, although their types become complex. It is concluded that the recirculating flows established behind the obstacle play an important role in holding the flame by transporting the fuel behind the obstacle and mixing it with the air.

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