Interaction of Two Micro-slot Flames: Heat Release Rate and Flame Shape

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Abstract. This paper studies the interaction between two identical micro-slot diffusion flames. Here, we define a micro-slot flame as a slot flame of which the slot width is less than about 1 mm. Because of its smallness, a micro-slot flame has a high heating density and can be used as a small heat source. However, the heat release rate of a single micro-slot flame is limited, and therefore, multiple micro-slot flames may be used to increase total heat release rate. As a first step, this paper considers a situation in which two micro-slot flames are used with certain burner spacing. When two diffusion flames are placed closely, flame shape changes from that of an isolated flame. Studying such flame shape change and resultant change in total heat release rate is the topic of this paper. Experiment is conducted and total heat release rate is measured by integrating CH* chemiluminescence recorded using a CCD camera and an optical filter of the wavelength of 430 nm. Two different burner materials, copper and glass, are tested to study the effect of heat loss to burners. An analytical model is applied to predict flame shape. In addition to the classical Burke-Schumann assumptions, two slot flames are modeled as line sources with zero width, enabling a simple analytical solution for the critical burner spacing at which two flames touch each other. The critical burner spacing is a key parameter that characterizes the interaction between two micro-slot flames. Computational fluid dynamics (CFD) simulations are then conducted to test the validity of the present theory. CFD results are favorably compared with the theoretical prediction.

1. Introduction

A jet diffusion microflame can be used as a small heat source [1-7]. In some applications, multiple microflames may be simultaneously used to enhance heating performance [8-10]. When multiple microflames are simultaneously used, the flames should not interfere with each other [10-12].

This paper studies the interaction of two identical micro-slot flames. A micro-slot flame is a flame on a slot burner whose width is less than about 1 mm, and an array of parallel micro-slot flames is capable of more uniform heating than that of circular-port microflames. Further, heat transfer behavior through the burner wall to the fresh fuel for a slot burner is different from a circular-port burner because of geometrical effects [5, 13-15]. Another aspect of interacting two slot flames is that

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they can be easily handled by a computational fluid dynamics (CFD) simulation because of their two dimensional nature, whereas the interaction between two circular-port flames is a three-dimensional phenomenon.

This paper focuses on the effects of burner spacing on flame shape and heat release rate. Experimental observations are first presented, followed by a simple model that predicts the flame shapes; the model is validated by comparing the model prediction with CFD results.

2. Experimental method

Figure 1 shows the experimental setup. Methane-air diffusion flames are established on two identical 1-mm-wide slots, each having 1-mm-thick burner walls. The distance between burner rims, is varied from 0 to 8 mm. The average exit velocity of methane is fixed at 40 mm/s.

Images of CH* chemiluminescence (hereinafter called CH* emission) are taken using a CCD camera with an optical filter of the wavelength of 430 nm. The intensity of CH emission is considered a good indicator of heat release rate for both premixed and diffusion flames.

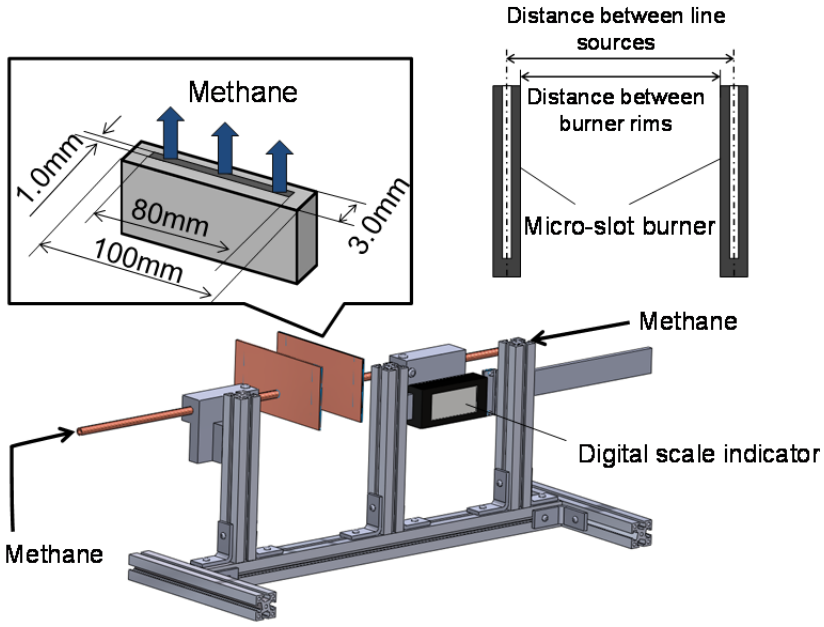

Figure 1. Experimental setup.

3. Experimental observations

Figure 2 shows integrated CH* emission (equivalently, total heat release rate). When the distance between burner rims is greater than about 5 mm, the total heat release rate is nearly constant, suggesting that each flame behaves similarly to an isolated flame as evidenced by the flame shapes shown in figure 3(a).

The total heat release rate tends to increase when the distance between burner rims decreases. This is mainly because with a decrease in the distance between burner rims, flame height increases (flame is established farther away from burners), reducing the heat loss to burners. Figure 3 shows that flame height increases with a decrease in the distance between burner rims. When the distance between burner rims is 0 mm and the two slot burners are in contact, the total heat release rate is increased by about 30% from the reference value. Under this condition, however, two flames merge into a single flame as shown in figure 3(d), losing characteristics as small-scale flames.

The local minimum of total heat release rate observed in figure 2 can be explained by heat loss to burners and local extinction. As shown in figure 3(c), the flames under a condition near the local

minimum are merged, and an inner flame and an outer flame are separately formed. The inner flame is much closer to the burners than the outer flame, being significantly influenced by heat loss. In addition, the tip of the outer flame is locally extinguished because of the inner flame's blocking effect of oxygen, further lowering total heat release rate. The influence of heat loss is also confirmed by the observation that the total heat release rate of glass burners is greater than that of copper burners; the latter material has a higher thermal conductivity and takes more heat from flame. From the experimental results thus far, predicting flame shape appears to be important when designing a device using multiple micro-slot flames.

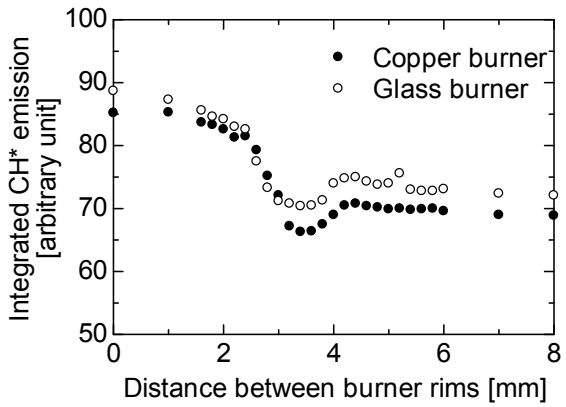

Figure 2. Integrated CH* emission and distance between burner rims.

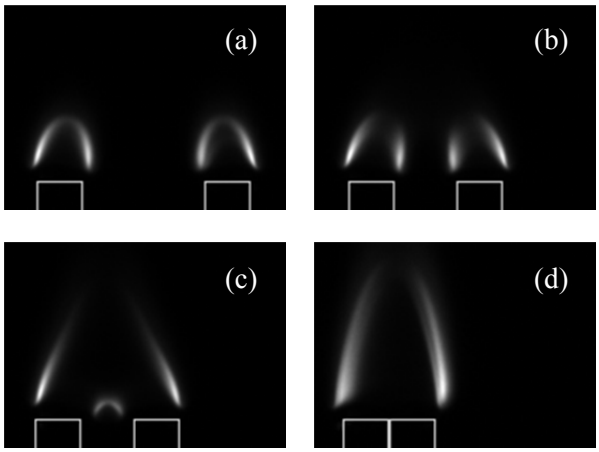

Figure 3. Flame shapes for different distances between burner rims: (a) 8 mm, (b) 4.4 mm, (c) 3.4 mm, and (d) 0 mm.

4. Line-source model

One of the simplest methods to predict the shape of a jet diffusion flame is to assume that the flow is uniform everywhere as in the pioneering study by Burke and Schumann [16]. They also assumed that thermophysical properties are constant, Lewis numbers for all species are unity, and the molecular transport terms in the flow direction is negligible. Analytical solutions for flame shapes were then derived; which have been confirmed to be qualitatively correct under various conditions. In this study, following Ref. [20], two micro-slot flames are modeled as diffusion flames in the uniform flow of velocity U.

When a typical combustible gas burns in air, $Z_{\mathrm{st}} \ll 1$, where Z_{st} is the stoichiometric mixture fraction. Then, the exit of a slot burner may be regarded as a line with zero width, and the following solution for the mixture fraction equation is obtained:

$$Z = \frac{Pe^{1/2}}{2\pi^{1/2}\bar{z}^{1/2}}\left[\mathrm{e}^{-Pe(2\bar{x}-\bar{a})^2/16\bar{z}} + \mathrm{e}^{-Pe(2\bar{x}+\bar{a})^2/16\bar{z}}\right] \tag{1}$$

where $Pe = UL/D$ is the Péclet number (L: slot width, D: diffusivity), and a is the distance between line sources. Overbar indicates that the variable is dimensionless in units of L.

Figure 4 shows flame shapes predicted by equation (1) for varied distance between line sources. It is confirmed that the present simple model can qualitatively reproduce experimentally observed flame shape shown in figure 3. From equation (1), the critical distance between line sources at which two flames touch each other is given by

$$a = \left(\frac{8}{\mathrm{e}\pi}\right)^{1/2}\frac{L}{Z_{\mathrm{st}}} \tag{2}$$

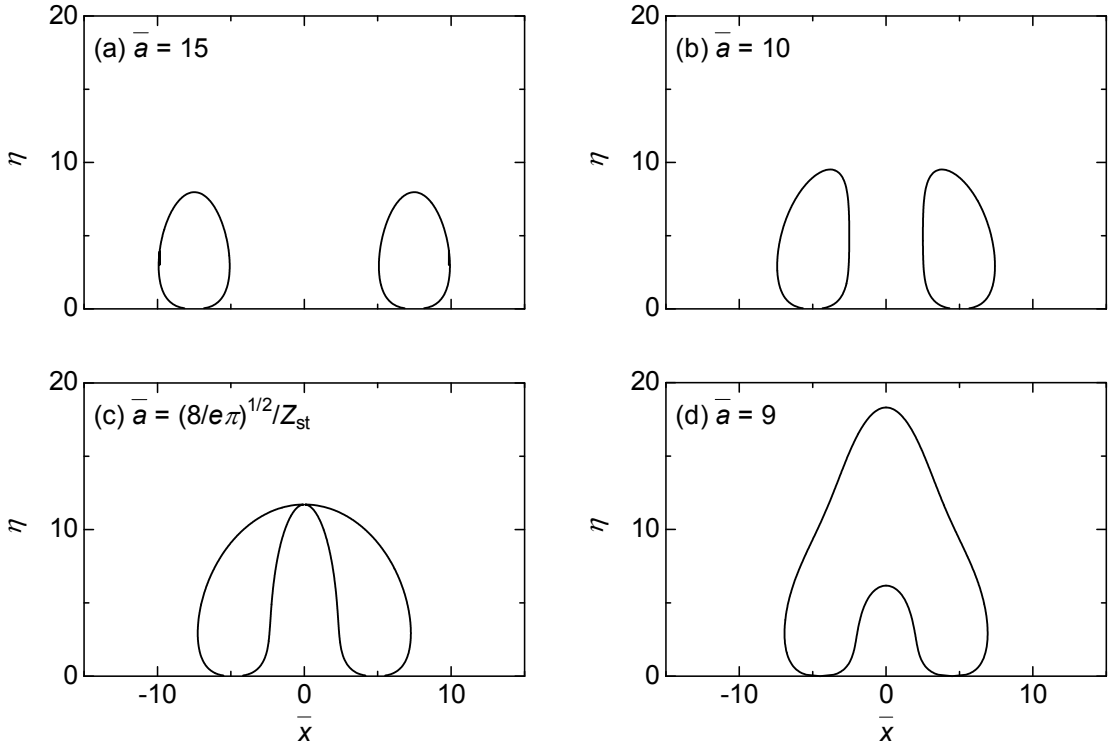

Figure 4. Theoretically predicted flame shapes, where $\eta = \bar{z}/Pe$.

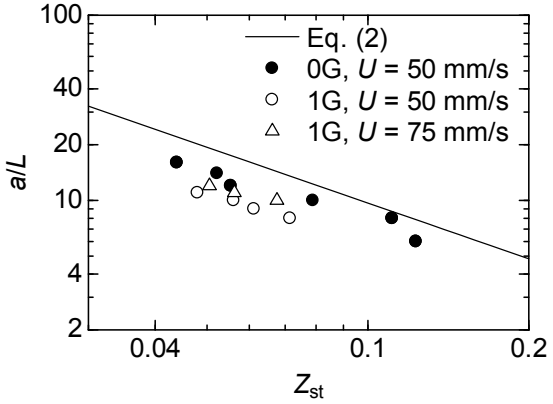

Figure 5. Validation of theoretical model comparing with numerical solutions.

5. CFD validation

This section tests the validity of model prediction, equation (2). Considering the difficulty in experimentally varying Z_{st}, CFD simulations are conducted. In CFD, Z_{st} can be easily varied by, for example, varying the oxygen mass fraction in the air. At the bottom of computational domain, inlet boundary conditions of methane and air with the same inlet velocity are adopted, similarly to the analytical model.

Figure 5 compares equation (2) with CFD predictions under various conditions. Overall, equation (2) predicts the dependence of critical distance between line sources on Z_{st} reasonably well. Since a uniform flow is assumed in the model, equation (2) predicts the same critical burner pitch for different gravity levels or fuel exit velocities, whereas the CFD result depends on these parameters. However, the dependence of critical distance between line sources on these parameters is rather weak, and equation (2) can be used for a first estimate.

Equation (2) tends to overestimate the critical burner pitch. A major reason for the error is because the model does not consider buoyant effects. Flow acceleration due to buoyancy tends to reduce the flame size, decreasing the critical burner pitch. This explains why the model works relatively well for 0G CFD results. Therefore, a remedy for the model is to consider acceleration due to buoyancy. Then, the model accuracy for predicting the influence of gravity level and possibly of fuel exit velocity will be improved; such a model will be studied in a later work.

6. Conclusions

The interaction between two identical micro-slot flames is studied. Experimental observations show that the total heat release rate basically increases with a decrease in burner spacing, but it has a local minimum. These trends are attributed to the shapes of the flames, indicating the importance of predicting flame shape. In particular, the critical distance between burner rims at which two flames touch each other is identified as a representative parameter to characterize the flame interaction. Experiments of different burner materials (copper and glass) further confirm heat loss effects on total heat release rate.

A simple analytical model is then developed to predict the flame shape and the critical burner spacing. The model assumes a uniform flow, similarly to the original Burke-Schumann model. In addition, two slot burners are modeled as two line sources to enable a simple analytical solution, from which the critical distance between line sources is obtained as a function of the stoichiometric mixture fraction. Considering the difficulty in experimentally changing the stoichiometric mixture fraction, CFD simulations are conducted to validate the analysis. The CFD results agree reasonably well with the analysis.

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