Microscopic Shadowgraph and CH-Band Emission Images of Micro-Jet Diffusion Flames

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Abstract

Micro-jet diffusion flames, formed by a minute burner of a few hundreds or a few tens μm inner diameter, should be interesting and useful, partly because they resemble micro-gravity flames and partly because they provide some insight into the mixing and chemical kinetic processes occurring in turbulent diffusion flames. The aim of the present experiment is to collect preliminary information on the characteristics and experimental techniques of micro-jet flames. Attention was paid to the effect of Reynolds number at the burner exit, and the range of Reynolds number that a stable flame could be formed was determined. CH-band images were recorded by direct photography, and compared with laser shadowgraph images.

Key Words: Micro-Jet Diffusion Flame, Lowest and Uppermost Flame-Stability Limits, Scale Effect on Flame Length and Shape

1. Introduction

In order to understand turbulent diffusion flames more completely, the information on their hierarchic structure ranging from microscopic to macroscopic scales is indispensable. The process of obtaining such information may be; first grasping the elementary flame structure, as well as the mixing and chemical kinetic processes for each hierarchy, and then finding out the rule to link each hierarchy. This process may lead us to the entire elucidation of the sophisticated mixing and combustion processes of turbulent diffusion flames, and may give us improved insight into the former experimental works, leading to new aspects of combustion engineering. The knowledge on the detailed microscopic structure of diffusion flames may not only explain the details of physical flame characteristics like flame stability limits or ranges, but also indicate the necessity of molecular combustion science or engineering, and may make our discussions deeper and more exact ones.

Ida and Ohtake [1], aiming at the elucidation of the microscopic flame structure of turbulent diffusion flames, applied the texture analysis technique to their two-dimensional laser Rayleigh scattering images of turbulent diffusion flames. They obtained instantaneous microscopic two-dimensional temperature patterns, and found that number of minute high-temperature clusters of about 20μm were embedded within the flame region near the flame axis. They, however, could not identify those clusters with micro diffusion flamelets.

Ban and his coworkers [2] studied laminar micro-flames and their structures. Their aim, however, was to control convective diffusion. Lockheed and his coworkers [3] studied the effects of gravity on laminar diffu-

Table 1 Micro flame burners and range of stable flame

No.	Inner diameter d (μ m)	Outer diameter D (μ m)	Range of stable flame	
			62.2%H_2+37.8%CH_4	CH_4
C1	40	100	not stabilized	not stabilized
C2	70	150	Re=226™~702	not stabilized
C3	100	200	Re=62™~2468	not stabilized
C4	300	800	Re=22～1407	Re=31～70
C5	700	1300	Re=9.9™~2001	Re=16™~100

sion flames. Unfortunately, their flames were somewhat different from the micro flames of the present study formed by micro burners of a few hundreds or a few tens μm inner diameter, so that direct comparison of both flames may be difficult. Interesting enough, the flame shape under a constant gravity (they used Fr number as the principal parameter) showed the tendency almost same as that of the micro flames, for which the effects of gravity is significant. They reported that the flame base was located somewhere below the burner port. This fact holds true also for the micro flames observed in the present study.

In the present study, the fuel-jet Reynolds number, calculated from the inner diameter of the burner and the mean fuel flow velocity, was taken to the principal hydrodynamic parameter. The range of Re number for a diffusion flame to be stabilized was determined, and the characteristics of resultant micro diffusion flames were observed using direct photography and laser shadowgraphy. If, in addition, some appropriate types of fuel are selected, chemical reaction-originated spatial distributions of CH-band emission and shadowgraph pattern may appear in the radial direction, and the characteristics of the flames may be observable.

Several micro burners, whose inner diameter was between 40 and 700μm, were used in the experiment as listed in Table 1. The uppermost- and lowest-limit Reynolds numbers for flame stability, which corresponded to flame blowout and flash quenching, respectively, were determined. The shapes and characteristics of various flames were observed, and found out some interesting flames, which had very special and unique characteristics. Since the aim of the present preliminary experiment was to collect fundamental data for micro flames and to establish the experimental technique for micro flames, attention was paid principally to the micro diffusion flames, which were close to the lowest-limit Re number and stabilized by a minute burner of a few or several tens μm inner diameter.

2. Apparatus and method

In the present experiment, two kinds of fuel were used; one was so called “Rayleigh fuel gas,” whose composition was 62.2%H_2+ 37.8%CH_4, and pure CH_4. The former keeps its scattering cross sectional area constant before and after combustion so that it is used for temperature measurement by Rayleigh scattering technique. The latter, pure CH_4, shows rather poor flame stability, but it is appropriate for flame zone visualization in terms of CH-band imaging. For the burners used, their inner and outer diameters are listed in Table 1 along with the Re-number ranges of flame stability for two kinds of fuel above. The length of each burner was between 150 and 1000 times the inner diameter, which was enough to eliminate the bend effects.

For flame visualization, direct photography and laser shadowgraphy were used. The optical system for the former is schematically shown in Fig.1. This simple system enables us to obtain up to 20 times magnified bright and sharp images. If the object flame is a soot-free blue flame, the images obtained may be taken to be CH-band images. The optical system for the latter, laser shadowgraphy consists of a He-Ne laser (beam power: 10mW) as the light source, and a 35mm still camera having a magnification rate up to 5 times. The laser beam was expanded up to the size enough for covering the view field (no optical lens was used to avoid the effects of interference with the incident beam), and projected onto a white paper through the object flame. The shadow image was photographed with the still camera.

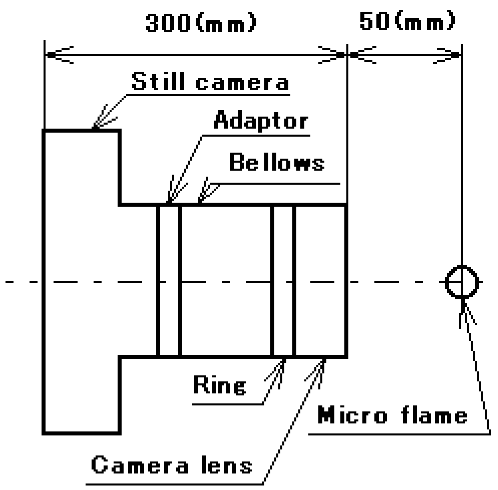


Fig.1 Direct photography system.

3. Results and Observation

Preliminary observations of the lengths and detailed structures of micro flames were conducted and described below. More detailed observations using various optical techniques and their comparison with numerical simulation may enable us to obtain the molecular dynamic aspects of laminar and turbulent diffusion flames.

3.1 Fundamental flame characteristics

The lengths, *L*'s, of micro flames listed in Table 1 were determined in terms of direct photography. The result is illustrated in Fig.2 for Rayleigh fuel gas, plotted against the Re number of fuel jet at the burner port (hereafter to be called "port Re number." The flame length increases linearly with the port Re number, and has a peak somewhere between Re=1000~2200, then decreases and finally blows out. The peak position shifts rightwards as the burner inner diameter decreases from 700μm to 100μm. *L/d* value is close to 150 for any burner. Burner C2 (*d*=70μm) is an only exception; its stability range is very narrow and has no peak in the flame-length curve.

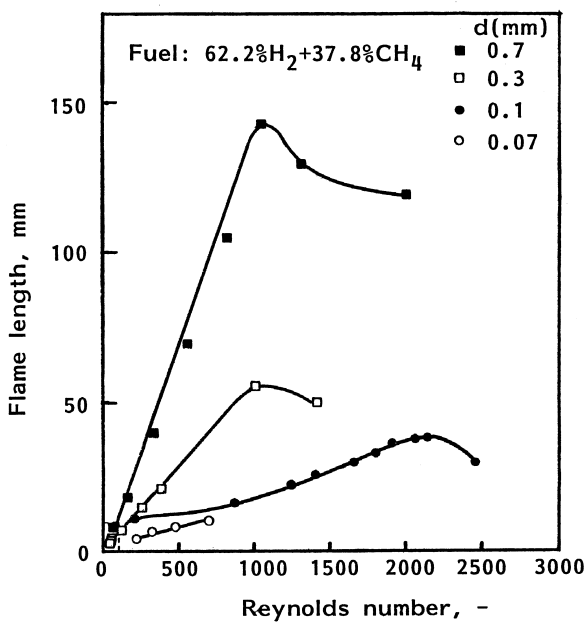


Fig.2 Flame length for Rayleigh fuel gas

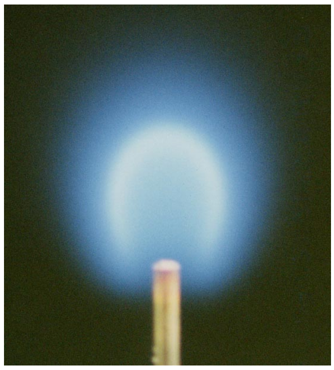
The curve for burner C5 (*d*=700μm) resembles to the well-known flame length curve (Hottel curve) for macro free-jet diffusion flames. In addition, the L/d value at the peak is about 150, which is typical for macro free-jet diffusion flames. However, no combustion noise peculiar to turbulent flame was perceptible.
The shape of flame length curve varied considerably as the burner inner diameter was decreased as seen in Fig.2. The linear portion, in the left side of the peak, of the curve deviated from a straight line, and the flame blows out immediately after having passed the peak. Combustion noise was perceptible only for burner C3 (*d*=100μm) and only close to the flame blowout condition (Re>2400, therefore the fuel flow is turbulent in the burner tube).

For burner C2 (*d*=70μm), the stable-flame region was considerably diminished to the range, Re=200~700. This region was extinguished if the burner inner diameter was decreased further down to 40μm (burner C1). This fact suggests that micro diffusion flames are much more dominated by molecular dynamic processes like molecular diffusion (subsequently by the Re number) and intermolecular collision as the burner scale is diminished. It also suggests the necessity to conduct experiments for fuels with a wide range of molecular diffusivity.

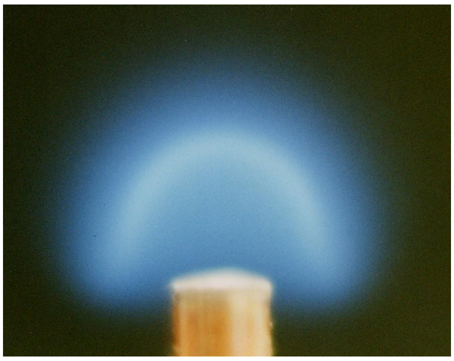
The variation in shape of the micro flames close to each lowest (flash extinction) limit as the burner inner diameter is varied is illustrated in Photo.1. These are direct photographs of Rayleigh fuel gas flames. Although no scale is shown, the flame size may be estimated from the outer diameter listed in Table 1. It may be noticed from these four photographs that the flame shape varies considerably depending on the burner scale. For burner C2 (*d*=70μm), the flame shape is a slender ellipsoid whose maximum width, *b*, is 800μm, whereas, for burner C3 (*d*=100μm), it is almost sphere and again *b*=800μm. For burner C4 (*d*=300μm), a hemispherical flame is seen, and b=2140μm. Almost the same flame is formed also for burner C5 (*d*=700μm), the flame shape in this case is considerably flattened.

When fuel was changed from Rayleigh fuel gas to pure methane, only burners C4 and C5 could stabilize a flame, and burners C1, C2 and C3 were not stabilized. With pure hydrogen, on the other hand, even burner C1 (*d*=40μm) could stabilize a diffusion flame. It is supposed therefore that the combustion process in a micro diffusion flame is dominated by molecular transport and molecular dynamic phenomena. A methane flame stabilized by burner C4 is shown in Photo.2. This is obtained by direct photography for a near lowest stability limit flame.

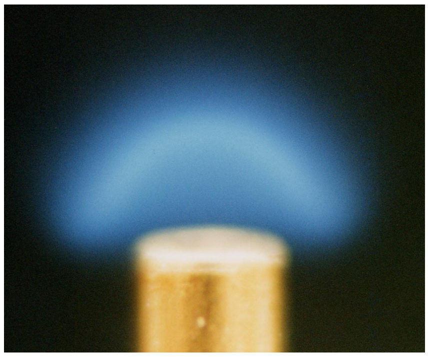
(a) d=70 µ m (C2)



(b) d=100 µ m (C3)



(c) d=300 µ m (C4)



(d) d=700 µ m (C5)

Photo.1 Scale effects on near lowest-limit flames (Rayleigh fuel gas and direct photography)

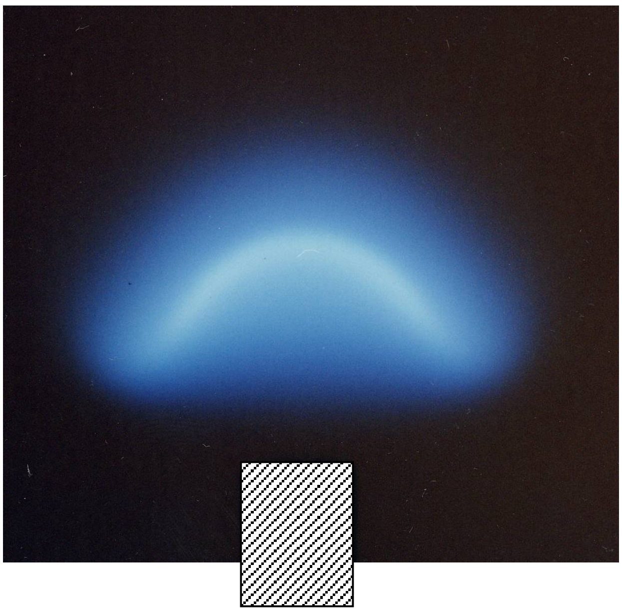


Photo.2 Direct photograph of CH_4 flame (burner: C4, d=300µm and near lowest limit condition at Re=31)

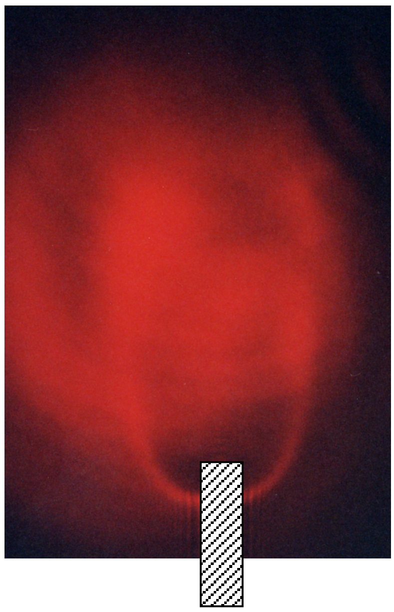


Photo.3 Shadowgraph image of CH_4 flame (burner: C4, d=300µm and near lowest limit condition at Re=31)

3.2 Comparison between direct photography and laser shadowgraphy images

Examples of laser shadowgraph images of a micro diffusion flame are shown in Photo.3. This is a methane flame stabilized by burner C4 (d=300μm) in a condition close to the lowest stability limit (Re=31). When this picture is compared with Photo.2 taken by direct photography under same experimental condition, it may be noticed that the image shape is completely different between these two kinds of photographing method. Further, the projection areas of the former are almost twice of the latter. It is supposed that direct photograph corresponds to blue or luminous flame zone, which emits CH-band luminescence, whereas laser shadowgraph involves preflame reaction region of high-temperature as well as blue or luminous flame zone. The preflame reaction region may exist just below the flame zone symmetrically. We are preparing the experiment to confirm the conjecture above.

4. Conclusion

Micro diffusion flames were stabilized by minute burners whose inner diameter was a few tens or a few hundreds μm. The lowest and uppermost limit Reynolds numbers for flame stability was determined. The length and shape of micro diffusion flames were observed by direct photography and laser shadowgraphy for two kinds of fuel. The variations in length and shape of micro diffusion flames were observed with the burner inner diameter and port Re number varied. The conclusions obtained are as follows.

(1) Micro diffusion flame can be stabilized by a burner of 70μm or larger inner diameter for Rayleigh fuel gas (62.2%H_2+37.8%CH_4), whereas methane flame can be stabilized only by a burner of 300μm or larger i.d. Hydrogen flame can be stabilized even by a burner of 40μm i.d.

(2) For Rayleigh fuel gas, the flame length increases linearly with the port Re number, and has a peak somewhere between Re=1000~2200, then decreases and finally blows out. The peak position shifts rightwards as the burner inner diameter decreases from 700μm to 100μm. L/d value is close to 150 for any burner.

(3) For Rayleigh fuel gas, the shape of direct photograph image of micro diffusion flame near lowest stability limit varies from a slender ellipsoid, through a sphere, to a hemisphere as the burner inner diameter increases from 70μm to 700μm.

(4) It is supposed that the combustion process in a micro diffusion flame is dominated by molecular transport and molecular dynamic phenomena.

(5) The image shape is completely deferent between direct photography and laser shadowgraphy. This fact seems to imply that a preflame reaction region exists just below the flame zone symmetrically.

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