Structures of Tubular Flames*

(Structures of the Tubular Flames of Lean Methane/Air Mixtures in a Rotating Stretched-Flow Field)

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The tubular flames of lean methane/air mixtures in a rotating-flow field have been analyzed for their concentrations of stable species and temperature distributions, and their structures have been investigated. The results show that the tubular flame consists of an inner hot gas core of burned gas and an outer region of the unburned mixture, and that the flame structure is essentially the same as that of one-dimensional, flat, premixed flame. As the extinction limit is approached, the flame diameter decreases and the concentrations of carbon monoxide and hydrogen behind the flame zone increase. Hence, the extinction of the tubular flame of lean methane/air mixtures is caused by incomplete combustion with stretch as it is with other stretched flames. As the density inside the flame is lower than that outside, the flame front is rendered smooth and cylindrical by the rotational motion of the flow.

Key Words: Combustion, Premixed Combustion, Tubular Flame, Flame Structure, Lean Mixture, Stretch, Rotating Flow Field

1. Introduction

Recently, the behavior of premixed flames in axisymmetrical flow fields has been investigated by using two types of simple burners, and it was found that an axisymmetric long tubular flame with a circular cross section could be established in rotating and nonrotating flow fields⁽¹⁾. Essentially, this flame is different from the plane, stretched flames obtained by a variety of burners^{(2)~(5)}, in the sense that the flame has a curvature; hence, this flame is very interesting from a fundamental point of view in combustion research. Also, it is important to note that the present study yields useful insights for understanding turbulent combustion because it is sometimes considered that turbulent combustion may occur within randomly

distributed vortex tubes of the diameter of the Kolmogorov microscale, which is subjected to stretching by vortices of the Taylor microscale^{(6),(7)}, while the flow field in which the tubular flame is established corresponds to such a stretched vortex flow. Therefore, recently, many experimental and theoretical studies have been made on the tubular flames, and the effects of flame stretch, fuel concentration, and Lewis number of the mixture on the extinction limit and flame diameter are studied^{(8)~(17)}. However, the structure of the tubular flame, especially the concentration profiles of stable species, has not yet been investigated because the tubular flame was discovered very recently.

Thus, as the first step of the research on the detailed structure of the tubular flame, we measure the concentrations of stable species in the tubular flame of lean methane/air mixture established in a rotating flow field, by using the conventional microprobe sampling technique and gas chromatography^{(18),(19)}.

2. Experimental

Figure 1 shows the experimental set-up used in

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this study. As in the previous study⁽¹⁾, the so-called swirl-type burner⁽²⁰⁾ is used. The inner diameter of the burner is 19 mm, which is bigger than the previous one (i.d. : 13.4 mm) to permit probing, while the width of the tangential slit and the length of the burner are 3 mm and 120 mm, respectively, which are the same as those of the previous burner⁽¹⁾. This burner geometry gives a swirl number of about 1.3, which is larger than that of 0.6 of the previous burner⁽¹⁾, and therefore, recirculation flow may occur⁽²¹⁾. However, the observation shows that the recirculation flows are confined in both regions of the burner ends. Thus, it can be considered that a simple rotating stretched flow field is established in a greater part of the burner, as the theoretical analysis⁽⁸⁾ indicates.

In this experiment, methane (99.8% pure) was used as a fuel. Fuel and air were supplied from a high-pressure bomb and a compressor, respectively, and introduced through orifices and flow control valves to mix. The homogeneous mixtures of fuel and air were fed to the burner. The orifices were calibrated by a wet gas meter (0.83~50 l/min) and a soap bubble meter (0.2~1.0 l/min).

The configuration of the flames was recorded by means of direct exposure photography. The temperature distributions were measured by a silica-coated Pt/Pt-13% Rh thermocouple (wire diameter : 0.1 mm), but no correction for thermometric error due to radiation and conduction was made. The two wires extruded 25 mm from the two-hole ceramic tube (outer diameter : 1.6 mm), which was horizontally held just as a cantilever.

The concentration profiles of stable species were determined using a microprobe sampling technique and gas chromatography. The samples were withdrawn through a quartz microprobe, which has an outer diameter of about 0.3 mm at the tip and an orifice diameter of about 20~30 μm . The pressure drop across the orifice was sufficient to quench the reaction. The sample probed from the flame was once stored in an evacuated sample assembly, and the concentration of various species was determined by using a gas chromatograph (Hitachi type 163 and Shimadzu type 3BT).

Chemical analyses for hydrogen, oxygen, nitrogen, carbon monoxide, carbon dioxide, water vapor, and various hydrocarbons were made using a molecular sieve (type 13X and 5A), activated charcoal, and Porapak (type S and N) columns. The carrier gas was helium or argon. The lines from the probe to the gas chromatograph were all heated to prevent water condensation. In the measured oxygen concentration, argon in the air is also included because helium is used as a carrier gas.

As shown in Fig. 1, the sampling microprobe was inserted parallel to the flame front to prevent a positional error and to minimize the concentration gradient effect⁽¹⁸⁾. Using a slidemovement, the probe was traversed in the direction normal to the flame front at a section near the center, and the radial distributions of the concentration profile were measured. The flame did not seem to be disturbed by the inserted probe due to the small probe size, nor the rereaction in the probe heated by the flame seemed to occur due to relatively low flame temperature.

3. Results and Discussion

3.1 Stability diagram of flame

For appropriate conditions of the fuel concentration ϕ (vol. % methane) and the mixture tangential velocity V_t (m/s), which is obtained by dividing the mixture flow rate by the exit area of the tangential slit, a long tubular flame with a circular cross section can be established, as shown in Fig. 2. The diameter of the flame is almost constant along the axis of the tubular flame except at both ends of the flame, where the flame is tulip shaped with sudden expansion by the swirling effect and a formation of recirculation zone. With an increase of fuel concentration while keeping the ejection velocity almost constant, the diameter of the flame is increased and a corrugation appears at the flame front. On the other hand, with decrease of the fuel concentration, the flame diameter is decreased, the luminosity of the flame is also weakened as shown in Figs. 3 (a)~(d), and the flame is eventually extinguished⁽¹⁾.

Figure 4 shows the mapping of the flame extinction limits and the boundaries for the corrugated tubular flame as the functions of the fuel concentration ϕ and the ejection velocity V_t . The fuel concentration at the boundary of the flame corrugation increases almost linearly with increasing V_t . The fuel

Fig. 1 Experimental setup

Fig. 2 Direct photographs of the tubular flame ($V_t=3.3$ m/s, $\Omega=5.59\%$, (a) front view and (b) side view)

Fig. 3 Photographs showing the variation of flame diameter ($V_t=3.3$ m/s, (a) $\Omega=5.30\%$, (b) $\Omega=5.20\%$, (c) $\Omega=5.10\%$, (d) 4.96%)

concentration at extinction slightly increases with increasing V_t , but takes an almost constant value ($4.8\sim 5.0\%$). This value is lower than the value of 5.3% previously obtained with a 13.4 -mm inner diameter burner⁽¹⁾, or the lean flammability limit of 5.0% ⁽²²⁾, and is almost equal to the value of 4.8% for the binary flame in the counterflow burner⁽⁴⁾. The reasons are that, essentially, there is minimal or no heat loss behind the flame because of the near symmetrical temperature distribution⁽¹⁾, and that the burner diameter used in the present experiment is larger than that of the previous burner, and hence, the heat loss to the burner wall seems to be small. Although the formation of recirculation flow may occur at both ends of the burner because of the large swirl number, the present burner offers an ideal minimal heat-loss condition for the flame.

Based on these results, we have chosen the following two flames for their structure measurements: a large-diameter flame of $\Omega=5.59\%$ at $V_t=3.3$ m/s (Fig. 2), and a small-diameter flame of $\Omega=5.10\%$ at

Fig. 4 Mapping of the response of the tubular flame as functions of the fuel concentration (Ω , % CH_4) and the tangential mixture ejection velocity (V_t)

$V_t=3.3$ m/s (Fig. 3(c)). In addition, in order to investigate the mechanism of flame extinction due to stretch, we measured the concentrations of the intermediate products (CO and H_2) around the center axis at a small stretch rate ($V_t=2$ m/s) and a large stretch rate ($V_t=6$ m/s), keeping the fuel concentration almost constant ($\Omega \approx 5\%$).

3.2 Concentration profiles of stable species and temperature distributions

Figures 5 and 6 respectively show the concentration and temperature distributions for the flame of $\Omega=5.59\%$ and that of $\Omega=5.10\%$ at $V_t=3.3$ m/s. Here, $r=0$ mm corresponds to the axis of rotation (which coincides with the center line of the glass tube) and $r=9.5$ mm to the burner wall.

For the case of $\Omega=5.59\%$ (Fig. 5), the luminous flame zone is located around $r=3.15\sim 3.60$ mm. The position of this luminous flame zone is photographically determined, and hence the thickness of the luminous flame zone may be varied by the film sensitivity and the exposure time. It may be seen that the combustion field is separated by this luminous flame zone into an outer region of the unburned mixture (methane/air mixture of room temperature) and an inner region of burned gas (the mixture of carbon dioxide, water vapor, excess oxygen, and nitrogen of high temperature). The concentration of methane is de-

creased from the outside towards the luminous flame zone, and becomes almost zero at the inner edge of the luminous flame zone. The concentration of oxygen also is decreased from the outside and becomes almost constant (9.5% including argon in air) inside the luminous flame zone. On the other hand, the intermediate products of hydrogen and carbon monoxide are increased from the outside. The hydrogen concentration reaches its maximum of about 0.14% at the outer edge of the luminous flame zone, and the carbon monoxide concentration reaches its maximum of about 0.98% at the inner edge of the luminous flame zone. Then, these concentrations decrease towards the inner flame zone and become very small (H_2 : 0.005%, CO : 0.006%) at the center line ($r=0$ mm). The concentrations of combustion products of water vapor

and carbon dioxide are gradually increased from the outside towards the luminous flame zone. The water vapor concentration reaches its maximum at the luminous flame zone and becomes almost constant (about 11.4%) inside the flame. The concentration of carbon dioxide reaches its maximum well inside the luminous flame zone and becomes constant (about 5.7%) inside the flame.

The temperature increases from the outside, reaches its maximum of 1180°C well inside the luminous flame zone, then slightly decreases at 1140°C around the flame core. Such a temperature decrease was not observed⁽¹⁾ when a small-diameter glass tube was used for the burner, nor was it seen in the small-diameter flame described below (Fig. 6). This temperature decrease seems to be due to the present probing. As the large-diameter glass tube is used for the burner, a recirculation flow probably occurs around the ceramic tube of the thermocouple. By the effect of the centrifugal force of rotation, the hot burned gas of low density is drawn inside the burner together with the cold air around the ceramic tube, which may increase the conductive heat loss from the flame.

It may be interesting to note that the species of C_2H_2 , C_2H_4 , and C_2H_6 , which are usually observed in diffusion flames, have not been detected at all in this flame, although various kinds of columns (activate charcoal and Porapak-type N columns) have been used. The concentration of nitrogen takes an almost constant value throughout the combustion field, which is because the molar number does not change in the global methane oxidation reaction.

From these results, it is clearly shown that although the present flame is established in the rotating stretched flow field, the structure is very similar to that of one-dimensional or quasi-one-dimensional (plane) premixed flames^{(18),(23)}. That is, methane is oxidized in two stages; first it is converted into hydrogen and carbon monoxide and then the carbon monoxide is slowly oxidized into carbon dioxide at the inner flame region. The burned gas compositions and temperature at $r = 0$ mm behind the flame zone (H_2O : 11.4%, CO_2 : 5.7%, O_2 : 9.5% (including argon), T : 1140°C (the radiative loss from the thermocouple is about 70°C if we use the equation for compensation of radiative loss in Ref. (24))), are almost the same as those of the calculated values (H_2O : 11.2%, CO_2 : 5.53%, O_2 : 8.5%, T : 1317°C) assuming the chemical equilibrium⁽²⁵⁾. Although the corrected temperature behind the flame is still about 100°C lower than the adiabatic flame temperature, the concentrations of hydrogen and carbon monoxide are very low at the center. Therefore, it can be considered that an almost

Fig. 5 Concentration profiles of stable species and temperature distributions of the tubular flame of $Q = 5.59\%$ at $V_t = 3.3$ m/s

Fig. 6 Concentration profiles of stable species and temperature distributions of the tubular flame of $Q = 5.10\%$ at $V_t = 3.3$ m/s

complete combustion is achieved as it is in the one-dimensional flame.

On the other hand, for the case of $\Omega=5.10\%$ (Fig. 6), the luminous flame zone is located around $r=1.7\sim 2.2$ mm, and the flame diameter becomes smaller than that of $\Omega=5.59\%$ flame (Fig. 5). However, the flame structure is almost the same as that for $\Omega=5.59\%$. Methane is oxidized into hydrogen and carbon monoxide at first, and then the carbon monoxide is slowly oxidized to carbon dioxide in the inner flame zone. However, the positions where hydrogen and carbon monoxide concentrations take their maxima are situated slightly outside of the luminous flame zone. Although their maxima ($H_2: 0.08\%$, $CO: 0.68\%$) are lower than those of the $\Omega=5.59\%$ flame, at the center axis ($r = 0$ mm), the hydrogen concentration is 0.006% and the carbon monoxide concentration is 0.048% . As an appreciable amount of carbon monoxide is left unburned, a complete reaction may not be achieved. The burned gas composition at $r = 0$ mm, is 10.6% H_2O , 5.55% CO_2 , 10.2% O_2 (including argon), 0.048% CO , 0.006% H_2 , and the temperature is $1090^\circ C$ (radiative compensation may be $60^\circ C^{(24)}$), while the composition and temperature calculated by assuming chemical equilibrium are 10.1% H_2O , 5.1% CO_2 , 9.7% O_2 , 0.80 ppm CO , 0.63 ppm H_2 and $1232^\circ C$. Although the measured flame temperature is about $80^\circ C$ lower than the calculated flame temperature, the concentrations of combustion product (H_2O and CO_2) are almost the same as the calculated values. Therefore, it is found that the major burned gas composition of the small-diameter (about 4 mm) flame ($\Omega=5.10\%$) is almost the same as that of the one-dimensional flame⁽¹⁸⁾ although the carbon monoxide concentration remains relatively high and hence complete combustion may not be achieved.

We further tried to probe a smaller-diameter flame. However, we could not measure the concentration profiles because the flame was completely or partially extinguished for probing. Although it seems that the effect of flame curvature on the extinction appears when the flame diameter becomes the order of flame thickness, the tubular flame at this time becomes much smaller due to its geometrical configuration than the flat, binary flame. The heat loss and the disturbance on the flow field by inserting the micro-probe cannot be disregarded. Therefore, some optical method is recommended for further detailed measurements.

3.3 The effect of stretch rate on the flame structure

The tubular flame suffers only from the stretch in the longitudinal direction as long as the cylindrical symmetry is maintained^{(1),(8)}. In order to examine the

effect of the stretch rate, we measured the concentrations of hydrogen and carbon monoxide around the center at $V_t=2$ m/s (low stretch rate) and $V_t=6$ m/s (high stretch rate) keeping the fuel concentration almost constant ($\Omega \approx 4.98\% \sim 4.99\%$) and examined the completeness of the combustion. The results are shown in Fig. 7, in which r' is the distance from the tube wall and $r'=9.5$ mm corresponds to the center axis of the burner. If we assume the following relation between the tangential velocity V_t and the radial velocity V_n as $V_n \cdot (\pi \cdot D_{id} \cdot l) \approx V_t \cdot A_t$ ⁽¹⁵⁾, in which D_{id} is the inner diameter of the burner (19 mm), l is the burner length (120 mm), and A_t is the tangential inlet slit area (3×120 mm²), the velocity gradient V_n/D_{id} , which is a measure of the flame stretch rate, is 5.3 s⁻¹ (at $V_t=2$ m/s) and is 15.9 s⁻¹ (at $V_t=6$ m/s),

Fig. 7 Concentration profiles of carbon monoxide and hydrogen around the center axis at conditions of (a) $V_t=2$ m/s (velocity gradient 5.3 s⁻¹), $\Omega=4.98\%$ and (b) $V_t=6$ m/s (velocity gradient 15.6 s⁻¹), $\Omega=4.99\%$

respectively.

It may be seen in Fig. 7(a) that when the velocity gradient is small, the concentrations of CO and H₂ are large near the luminous flame zone, while they are small at the axis of rotation; therefore, the combustion seems almost complete. However, when the velocity gradient is large (Fig. 7(b)), these concentrations are large even at the axis of rotation; hence, the combustion seems to be incomplete. The diameters of the flames are almost the same, which is probably because the fuel concentration for the flame of large velocity gradient is somewhat larger than that for the flame of small velocity gradient.

From the measurements above, it may be concluded that the tubular flame of the lean methane/air mixture is extinguished due to incomplete combustion caused by flame stretch as it is in the other stretched flat flames⁽²⁾⁻⁽⁴⁾.

Since the stream tube diverges as the axis of rotation is approached, the stream tube across the flame zone diverges in the tubular flame geometry. Especially, the extension of the stream tube is very large near extinction because the flame diameter is small. Therefore, through a stream tube, heat is taken away from the reaction zone by conduction while the deficient, hence controlling reactant is carried into the reaction zone by diffusion⁽¹⁾. In the present flame, the deficient reactant is methane, and its Lewis number is less than unity⁽²⁾. Therefore, the in-flow of the deficient reactant into the reaction zone exceeds the out-flow of heat from the reaction zone, resulting in an intensification of reaction. As a result, the tubular flame can stand the incompleteness of reaction and the flame diameter can become small until extinction. The flame is extinguished when the imbalance between the mixture velocity and the chemical reaction rate occurs.

3.4 Density distributions

Finally, based on the results shown in Figs. 5 and 6, the density distributions across the flame zone are calculated and shown in Fig. 8. In both flames, the density is low inside the flames and monotonically increases towards the outside to become about 4.5 times as large as those at the center. This density distribution is aerodynamically stable according to the Rayleigh stability criterion for radial momentum exchange^{(26),(27)}. Thus, it is confirmed that the tubular flame field is very stable whether the flame is situated in the forced vortex region near the axis of rotation or in the free vortex region which is only naturally stable according to the stability criterion. Although the tubular flame established in a nonrotating flow field is deformed by the buoyant force working on the hot burned gas or by the cellular instability due to prefer-

ential diffusion^{(1),(12)}, the tubular flame in a rotating flow field is relatively cylindrical in its cross-sectional shape. This is attributed to an interaction between the rotational motion and the density distribution shown in Fig. 8. In Fig. 4, it is shown that the tubular flame region with a uniform flame front becomes wider as V_t is increased. This may be due to a suppression of the flame front deformation by the rotation just mentioned, while the flame stretch, which increases with increasing V_t , may also suppress the deformation⁽²⁸⁾.

4. Conclusions

In order to investigate the structure of tubular flames established in an axisymmetrical stretched flow field, we measured, as a first step, the concentration profiles of stable species in the tubular flames of lean methane/air mixtures obtained by a swirl-type burner by using a microprobe sampling technique and gas chromatography. The main results obtained are as follows:

(1) It has been clearly shown by the present concentration measurements that the tubular flame consists of an inner region of burned gas and an outer region of the unburned mixture with a luminous flame zone between them.

(2) The typical two-stage oxidation of methane has been observed as in the other flames; the intermediate products of hydrogen and carbon monoxide are produced around the luminous flame zone, and carbon monoxide is slowly oxidized to carbon dioxide in the inner flame region.

(3) In the two flames, whose diameters D are larger than their thicknesses of the luminous flame

Fig. 8 Density distributions in the tubular flames ($V_t = 3.3$ m/s)

zone ((1) $\Omega=5.59\%$, $V_t=3.3$ m/s, $D=6.8$ mm, (2) $\Omega=5.10\%$, $V_t=3.3$ m/s, $D\approx 4$ mm), the burned gas compositions are in good agreement with the values calculated by assuming chemical equilibrium, although the temperatures behind the flame are about $80^\circ\text{C}\sim 100^\circ\text{C}$ lower than the adiabatic temperatures. Therefore, the structure of the tubular flame is almost the same as that of usual flames.

(4) In the case of the tubular flame of small diameter, in which the effect of curvature on the flame behavior seems to be remarkable, the flame tends to be extinguished completely or partially by probing, and hence, the structure could not be measured. For determining the structure of the tubular flame of small diameter, the order of which is the same as the thickness of the luminous flame zone, some other nonprobing method such as spectroscopy is recommended.

(5) In the case of the tubular flame of lean methane/air mixtures, with decreasing fuel concentration or increasing ejection velocity, the flame diameter decreases and the flame is eventually extinguished. Near extinction, the concentrations of hydrogen and carbon monoxide at the inner flame region are much larger than the values calculated by assuming chemical equilibrium, and they increase more as the extinction limit is approached. Therefore, the extinction of the tubular flame of the lean methane/air mixture seems to be caused by the incomplete combustion as in the other flat, stretched flames of lean methane/air mixtures.

(6) Based on the concentration and temperature profiles, the density distributions across the flames are obtained. The density monotonically increases from the inside out and reaches a value about 4.5 times as large as that in the core. This density distribution makes the tubular flame aerodynamically very stable for rotational motion, and the flame distortion caused by the buoyant force or the cellular instability is considered to be suppressed by increasing the intensity of rotation.

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