Observations on the mixing process between an inner cold air stream and an outer swirling tubular flame stream

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Abstract In this study, a burner with variable swirl intensity has been newly made and the flow field has been visualized in detail under cold conditions and, in addition, under combustion conditions. One of the important findings by the visualization is that at a given combination of the flow rates of the inner, cold waste gas stream and the outer, hot swirling stream, the inner stream keeps its shape far downstream for the swirl number S=0.35, but shows instability for S=0.7, and bifurcates just downstream the inlet position for S=1.4 under combustion conditions, although they are all well mixed under cold flow conditions. The dependency of the flow condition on the swirl number is in good agreement with the previous results obtained in the swirl-type tubular flame burners, and also well explains the result that the heating rate for the inner stream is lower for S=0.35, moderate for S=0.7, and higher for S=1.4. In addition, the effects of swirl number on the heating process has been discussed based on a simple analysis and it is demonstrated that the enhancement of heating with swirl can be described mainly through an increase of the heat transfer area between the cold waste stream and the swirling hot burned gas stream through involvement of a rotational motion.

Keywords: Tubular Flame, Swirl, Heating, Laminarization, Mixing

1 Introduction

In today's semiconductor industries, many kinds of dangerous gases such as flammable gases, pyrophoric gases, and toxic gases are used. These gases definitely cause health hazard for manufacturing workers and, if exhausted outside, aggravate air pollution and global warming. Thus, these gases should be carefully purified through a post-processing device such as a combustion treatment device and a purification catalyst [1]. These post-processing devices are, however, energy- and cost-consuming. To solve this problem, a new, innovative post-processing system is desired. Recently, a new abatement system has been developed [2] (see Fig.1). This system has adopted a tubular flame [3] and the waste gas has been introduced into the inner hot gas region of a tubular flame. It has been found that NF₃ gas has been successfully decomposed in this tubular flame system, however, present knowledge is inadequate. Up to now, several fundamental studies have been made on this subject. It has been found that the rate of heating of the waste gas is enhanced as the swirl number of the burner is increased [4-6]. Flow visualization has been made although under cold flow conditions, and it has been found that due to the roll-up motion in the swirling flow of the tubular flame burner, the waste gas stream is entrained into the hot burned gas of the tubular flame, resulting in the enhancement of the heat transfer rate between the two streams.



Figure 1. Hazardous exhaust gases post-processing system with a tubular flame [2].

In this study, a burner with variable swirl intensity has been newly made and the flow field has been visualized in detail under cold conditions and, in addition, under hot flow conditions. In addition, to understand the effects of swirl number on the heating process, a simple calculation have also been examined.

2 Experimental

Figure 2 shows the schematic drawing of the tubular flame burner used in this experiment. The burner is made of brass, which consists of eight rectangular slits and a downstream quartz tube. The inner diameter of burner is 40 mm, while the slit length (L) and width (W) are 50 and 5 mm, respectively. In order to get different swirl intensities, the slit number is changed from 8 to 4, 2 by closing slits, leading to the swirl numbers S of 0.35, 0.7 and 1.4 [3], respectively. At the closed end of the burner, a stainless pipe of 8 mm inner diameter D_{inj} , is connected to pass the air to be heated along the central axis. At the open end of burner, a quartz tube of 300 mm long and 40 mm inner diameter, which is the same as that of the tubular flame burner, is attached.



Figure 2. Schematic of the tubular flame.

The fuel used is methane while the oxidizer used is air. The flow rates of the fuel and the air are metered with orifice flow meters, well mixed, and then fed to the burners. The unit of flow rate is m³/h at STP condition. To observe flames inside the burners, a quartz window, instead of the stainless pipe, is installed at the burner, and flames are photographed simultaneously with two digital video cameras.

In order to investigate quantitatively how fast the air is heated for different swirl intensities, radial and axial temperature distributions are determined with a silica-coated Pt/Pt-13%Rh R-type thermocouple (wire diameter: 200 μ m). But in this study, radiation correction for thermometric errors is not made. For these measurements, a stainless steel tube of 36 mm inner diameter and 300 mm long is attached with the burners instead of the quartz tube (see Fig.2). The stainless steel tube is pierced at distances 75, 125 and 220 mm from the plane where the air to be heated is injected through the 1/4 inch pipe, denoted as Z_1 , Z_2 , and Z_3 respectively.

3 Results

3.1 Appearance of flames

Figures 3 shows the appearances of flames when a premixture of methane/air is injected into the burner with variable swirl intensity, in which the air flow rate for combustion is kept constant at $Q_{air}=10 \text{ m}^3/\text{h}$.

In Fig. 3 (a)-(c), the left pictures are taken through the quartz window (denoted as Front View) while the right pictures are taken through the quartz tube (denoted as Side View). The middle is an illustration showing the positions of the tangential slits, the quartz window, and the position of the tubular flame (solid red lines), which is close to the tangential slit for the stoichiometric mixture (middle), the flame approaches the center line for the rich (upper) and lean(lower) mixtures.

It is seen in Fig. 3 that tubular flames of cylindrical cross section and almost constant diameter can be established. When the mixture is stoichiometric, the burning velocity is high. Then the flame diameter becomes large and the cross sectional shape is deformed likes a separated circular shape, while the flame becomes short in length (Fig.3 middle). Note that the luminosity around downstream of the quartz tube is due to the thermal radiation from a hot burned gas. When the mixture becomes richer or leaner, the flame

becomes smaller in diameter while larger in length simply because of a decrease of the burning velocity (Figs.3 upper and lower). For the rich condition, the flame color is blue-green, while for the stoichiometric and lean conditions, the flame is blue in color. With further increasing or decreasing fuel flow rate, the flame is eventually extinguished around at the rich or lean flammability limits.





Figure 4 shows the appearance of flames obtained with the tubular flame burners of different swirl numbers, when a heated air is injected from the stainless pipe at a flow rate Q_{inj} of 0.5 m³/h, while the flow rate of the air for combustion and the equivalence ratio are kept at $Q_{air}=2.0$ m³/h and $\Phi = 0.7$. Note that the right pictures (denoted as Rear View) are taken from the end of the quart tube.

In the case of the swirl number of S = 0.35 (Fig. 4a), a separated flame is anchored at each exit of the tangential slit though which a premixture of methane/air is injected. This is due to the small radial velocity $V_{\rm w, mix}$, which is 11.8 cm/s, much less than the burning velocity $S_u = 22$ cm/s at $\Phi = 0.7$ [7]). The flame extends slightly to the quartz tube, which can be seen in the left picture.

With an increase of the swirl number to S = 0.7 and 1.4, the tangentially-injected velocity is increased and each flame anchored at the slit extends; however, they are still separated as shown in the right pictures of Figs.4b and 4c. In both the cases, the flames, however, extend downstream in the quartz tube, and eventually, the separated flames are connected; a smooth continuous, tubular flame is formed in the quartz tube.



Figure 4. Flame appearances of methane/air mixtures for premixted with the air to be heated $Q_{air}=2.0 \text{ m}^3/\text{h}$; $\Phi=0.7$, $Q_{inj}=0.5 \text{ m}^3/\text{h}$.

3.2 Radial and axial temperature distributions

Next, to examine how well the tubular flame works for the heating, radial temperature distributions have been determined. The results at three positions, $Z_1=75$, $Z_2=125$, and $Z_3=220$ mm are shown in Fig.5, in which $r=\pm 18$ and 0 mm correspond with the burner wall and center axis, respectively. In these measurements, an air to be heated is injected at the same flow rate of Fig.3right, 0.5 m³/h, i.e., the mean injection velocity is about 2.76 m/s.

At $Z_1 = 75$ mm (Fig.5a) and in the case of swirl number of S = 0.35, the temperature is around 500 degree C near the wall ($r = \pm 18$ mm), then, increases towards the center (r = 0 mm), and reaches its maximum of 1250 degree C at $r = \pm 12$ mm. As seen in Fig.5a, the tubular flame is formed around the inner periphery of the tangential slit, which has 5 mm in width, thus the highest temperature position corresponds with the location of the tubular flame. As the center is approached, the temperature is decreased and just 100 degree C at the center. When the swirl number is increased to 0.7, the obtained temperature distribution is similar to that of the swirl number of 0.35. When the swirl number is further increased to 1.4, however, the temperature at the center dramatically increased and its vale is about 750 degree C.

At $Z_2 = 125 \text{ mm}$ (Fig.5b) and $Z_3 = 220 \text{ mm}$ (Fig.5c), for the former, the temperature at the center is increased as the swirl number is increased. That is, the temperature is increased to about 450 degree C for S = 0.35 and S = 0.7, while the temperature is increased high 900 degree C for S = 1.4. for the latter, the temperature is not so increased and 850 degree C for S = 1.4. It should be noted that the expected final temperature due to the mixing of the cold air injected through the stainless pipe and the burned gas of the swirling tubular flame is 1323 degree C. If heat loss to the burner wall is taken into consideration, the temperatures at the center seems to reach their maxima for S = 0.7 and 1.4, while it has not yet reached for S = 0.35. Thus, as seen in our previous measurements [4, 5], the central stream can be heated more swiftly with a tubular flame if the swirl number is increased.



 m^{3}/h ; (a) Z₁=75 mm, (b) Z₂=125 mm (c) Z₃=220 mm.

3.3 Flow visualization

First, flow visualizations have been made under cold flow conditions to discuss the swirl number effect on the flow field.

Figure 6 left shows the flow visualizations at the cross section of $Z_1 = 75$ mm and in the plane containing tube axis for the burners of different swirl numbers. In these visualizations the air flow rate for combustion is kept constant at $Q_{air} = 0.16 \text{ m}^3/\text{h}$ and the air flow rate to be heated is kept at $Q_{inj} = 0.16 \text{ m}^3/\text{h}$. It should be noted that only the air to be heated is seeded with MgO particles.

In the case of S = 0.35, the central seeded air stream keep its circular shape and the diameter remains almost constant downstream from $Z_1 = 75$ mm to $Z_3 = 220$ mm (Fig.6, left (a) Rear View, (a') Side View). With an increase of the swirl number to 0.7, the seeded air stream keep the same circular shape as that of S = 0.35 at $Z_1 = 75$ mm (Fig.6, left (b) Rear View), whereas the seeded air stream is attenuated a little and shrinks at $Z_3 = 220$ mm (Fig.6, left (b') Side View). When swirl number is further increased to 1.4, it is seen that the outer swirling air stream is involved into the seeded air stream due to the roll-up motion of the swirling stream (Fig.6, left (c) Rear View). It should be noted that around $Z_2 = 125$ mm the seeded air stream is broken up due to the instability in the tangential direction (Fig.6, left (c') Side View).

In order to understand the increase of the temperature rise observed in Fig.5, flow visualizations have been made at the same condition of Fig.5, i.e., $Q_{air} = 2.0 \text{ m}^3/\text{h}$ and $Q_{inj} = 0.5 \text{ m}^3/\text{h}$. The results are shown in Fig.6 right. When the flow rates of the two streams are increased, the mixing is much enhanced. The two

streams are well mixed for all the three swirl number as compared with those of the smaller flow rates of Fig.6 left. At Z_1 = 75 mm, however, the cross-sectional views (Fig.6 right d, e and f) show that the two streams are still separated and the mixing is promoted with an increase of the swirl number.



Figure 6. Flow visualization under cold flow conditions (left) $Q_{air}=0.16 \text{ m}^3/\text{h}$, $Q_{inj}=0.16 \text{ m}^3/\text{h}$; (right) $Q_{air}=2.0 \text{ m}^3/\text{h}$, $Q_{inj}=0.5 \text{ m}^3/\text{h}$.

Under combustion conditions, however, the flow field is significantly changed. The flow visualization results at the same condition of Fig.5 ($Q_{air} = 2.0 \text{ m}^3/\text{h}$, $\Phi = 0.7$, $Q_{inj} = 0.5 \text{ m}^3/\text{h}$) are shown in Fig.7 left.

As seen in the cross-sectional views at $Z_1 = 75$ mm (Fig.7 left upper), the seeded air stream keeps an almost circular shape for all the swirl numbers. In the side view, the centre cold air stream and the outer hot swirling gas stream are well separated and ordered even until $Z_3 = 220$ mm for S = 0.35 (Fig.7 left (a)). This may be resulted from the so-called laminarization in rotating environment [8-10].

In the case of S = 0.7, however, the seeded air stream snakes its way as seen in Fig.7 left (b). When the swirl number is further increased to 1.4, the seeded air stream begins to disperse around $Z_1=75$ mm, and the mixing of the two air streams is enhanced. Since the temperature at the center is already heated to 750 degree C in the case of S = 1.4, it is important to note that under hot flow conditions, the central air stream is heated under a laminar-fashion flow condition, different from the turbulent flow observed under cold flow condition (Fig.6 right).



Figure 7. Flow visualization under with different swirl numbers under combustion condition (left) flow visualization; (right) mean velocity profiles in tube axis plane for various swirl numbers; $Q_{air}=2.0 \text{ m}^3/\text{h}$, $\Phi=0.7$, $Q_{ini}=0.5 \text{ m}^3/\text{h}$

Figure 7 right shows are the mean vector profiles along the tube axis. This vector profiles supports our observation of Fig.7 left. In the case of S = 0.35 (Fig.7 right (d)), the seeded air stream is laminarized and ordered in the axial direction all the way to $Z_3 = 220$ mm. It should be noted again that different from the cold flow condition, the seeded air stream is suppressed in the radial direction. The expansion of the swirling burned gas may work for the suppression in addition to the laminarization effect in rotating environment. When the swirl number is increased to 0.7, however, the axial velocity on the center line slows down around Z = 150 mm (Fig.7 right (e)). When the swirl number is further increased to 1.4, the seed air stream slows down around $Z_1 = 75$ mm, and the two streams downstream are well mixed (Fig.7 right (f)).

These observations and vector profiles may elucidate our recent hypnosis that the enhancement of the heating rate with an increase of the swirl number can be explained mainly through an increase of the heat transfer area between the two streams accompanied with the rotational motion of the swirl burner [11].

4 Discussion

To discuss the effects of swirl number on the heating process with a tubular flame, a simple analysis has been made. Usually, the variation of mean temperature of a fully developed laminar flow in a circular tube under a condition of constant wall temperature is given by the following equation [12].

$$T(Z) = T_{\rm w} - (T_{\rm w} - T_{\rm i}) \exp\left(-\frac{h\pi D}{\dot{m}C_p} \frac{Z}{1000}\right)$$
(1)

in which T_w is the wall temperature, T_i is the inlet fluid temperature, h, D, \dot{m} and C_p are the heat transfer coefficient, the inner tube diameter, the mass flow rate and the specific heat at constant pressure of the fluid, respectively.

In this study, the mass flow rate of the air to be heated is 0.7×10^{-3} [kg/s]. As the specific heat, the value of 1.122 [J/kg·K] at 900K is used for calculation, because it does not change significantly between 320 and 1500K. The heat transfer coefficient *h* is given as $h = Nu \lambda/D$, in which λ : is the thermal conductivity and *Nu* is Nusselt number. As for *Nu*, we use 3.657 for a fully developed laminar flow with constant temperature at infinity. As for T_w , we use three representative temperatures, i.e., 700K, 1100K and 1500K, respectively. As for λ , we use the values at three representative temperatures, i.e., 51.3, 71.7 and 87.0[mW/m·K] at 700, 1100, and 1500K, respectively, since λ changes significantly with temperature. The results of calculation are shown in Figs.8a and 8b. It is seen that the analytic solutions well describe the experimental results of the burner of *S*=0.35 qualitatively, and that quantitatively, the calculation with λ at 1100K and T_w in 1500K is consistent with the experimental results. Then, based on the analytic solution of Eq.(1), we discuss the effect of swirl on the heating process.



Figure 8. Predicted axial temperature distributions for the representative heat transfer areas.

According our previous study [13], the heat transfer area is increased with the swirl number. The right graph of Fig. 8c shows the results, in which the heat transfer area πDZ is increased stepwise as $1.35 \pi DZ$, $1.7 \pi DZ$ and $2.4 \pi DZ$ in Eq. (1). It is interesting to note that the results with the analysis have a good agreement with the measurements of $1.35 \pi DZ$, $1.7 \pi DZ$ and $2.4 \pi DZ$ are in good agreement with the experimental results of S = 0.35, 0.7 and 1.4, respectively.

5 Concluding Remarks

In this paper, in order to obtain fundamental knowledge on the heating system with a tubular flame, a burner with variable swirl intensities has been made and the effects of the swirl number on the flame characteristics and the temperature fields have been experimentally investigated. In addition, using a PIV system, the flow fields are visualized in detail under combustion condition as well as under cold flow conditions to discuss the heating process in detail. One of the important findings by the visualization is that at a given combination of the flow rates of the inner, cold waste gas stream and the outer, hot swirling stream, the inner stream keeps its shape far downstream for the swirl number S=0.35, but shows instability for S=0.7, and bifurcates just downstream the inlet position for S=1.4 under combustion conditions, although they are all well mixed under cold flow conditions. The dependency of the flow condition on the swirl number is in good agreement with the previous results obtained in the swirl-type tubular flame burners, and also well explains the result that the heating rate for the inner stream is lower for S=0.35, moderate for S=0.7, and higher for S=1.4. In addition, the effects of swirl number on the heating process has been discussed based on a simple analysis and it is demonstrated that in accordance with the present flow visualization under combustion conditions, not under cold flow conditions, the enhancement of heating with swirl can be described mainly through an increase of the heat transfer area between the cold waste stream and the swirling hot burned gas stream through involvement of a rotational motion.

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