Effect of Flow Field on NOx Emission Properties of Jet Nonpremixed Flames in Cylindrical Furnaces*

Susumu NODA**, I Gede PARWA THA***, Yuzuru NADA**, Shigenori NISHIO*** and Shingo FUKUSHIGE***

** Department of Mechanical Engineering, Toyohashi University of Technology
Tempaku, Toyohashi, Aichi 441-8580, Japan
*** Graduate School of Engineering, Toyohashi University of Technology
Tempaku, Toyohashi, Aichi 441-8580, Japan

Abstract
The flow field characteristics of confined flames have been investigated for propane nonpremixed flames in cylindrical furnaces. The effects of furnace inner diameter \(D_1\), air inlet velocity difference \(\Delta U_a\), and global equivalence ratio \(\phi\) on the flow field are related to NOx emission. The emission index of NOx, \(E_{INOx}\), decreases roughly with the increases of the above parameters. This decrease is observed as a consequence of flame stretch and dilution by the burned gas. The flame stretch is related to the velocity difference introduced by multiple inlets, and the dilution is attributable to the recirculation structure formed at the bottom of the furnace. The present investigation shows the mechanism of burner/chamber configuration inciting the flow field and indirectly controlling NOx emission.

Key words: Turbulent Nonpremixed Flame, Furnace Combustion, NOx Emission, Exhaust Gas Recirculation, Chamber Size, Global Equivalence Ratio, Turbulence

1. Introduction
A number of combustion techniques have been developed, and various improvements to combustion techniques in terms of the reduction of NOx emission, including lean-rich combustion, slow mixing combustion, two-stage combustion, and flue gas recirculation combustion, have been proposed. NOx reduction methods using preheated and diluted air combustion (1) are widely used in practical applications. This reduction technology uses exhaust gas recirculation to decrease flame temperature and oxygen concentration. In confined combustion systems, burned gas self-recirculation flows naturally take place as a result of wall confinement. Implementation of laboratory-scaled analysis to industrial or other technical applications requires a scaling law. NOx scaling for nonpremixed flames under the stretch effect have been investigated by Driscoll et al. (2) with no consideration of the effect of the self-recirculation of burned gas.

The investigation of confined jet flows began in the 1950’s (3)(4). In confined jets, a limited supply of surrounding fluid would induce the formation of a recirculation structure between the jet and the furnace wall. Unlike open jets, confined jet flows undergo entrainment of recirculated fluid at the jet boundaries. The detailed flow structure of such jets was described by Curtet (5). The recirculation structure in the cylindrical furnace is similar to the structure investigated on backward-facing steps or dump combustors. Chen et al. (6) found an increase in recirculation structure size with the step height. Guo et al. (7)
numerically investigated the effect of heat transferred to the recirculation structure in a sudden expansion cylinder and showed that the changes in heating location and heating intensity affect the recirculation size.

The present paper reports the flow field characteristics of confined jet nonpremixed flames as a complement to previous studies \(^{(7)(8)}\). These studies revealed that NOx emission would significantly decrease by increasing the inner diameter of the furnace, increasing the turbulence at the flame boundary, and increasing the global equivalence ratio. The influence of recirculation vortices generated on the basis of a confined configuration was reported to be a major contribution to the dilution by the burned gas. In the present paper, the flow fields of confined jet nonpremixed flames are presented in order to complete the understanding of the combustion characteristics in cylindrical furnaces.

### 2. Experimental Apparatus

Figures 1 and 2 show the experimental apparatus used for the measurement of velocity fields. Pyrex tubes of previous investigations \(^{(7)(8)}\), which were used as furnace walls, are replaced by steel cylinders with inner diameters \(D_1\) of 92 mm and 180 mm, respectively. The replacement of the furnace resulted in a slight increase in NOx on the basis of the decrease in the radiation heat loss. Each furnace has a pair of quartz windows of 600 × 55 mm\(^2\), each with a thickness of 2 mm, on the front and back sides for laser Doppler measurements (TSI, IFA 755). The temperature was measured by a thermocouple of Pt-Pt/13%Rh having a diameter of 0.1 mm. The leading wire was cooled by water. The burner consists of a fuel nozzle with an inner diameter (i.d.) \(d_f\) of 2 mm, surrounded by coaxial air nozzles of 12 mm i.d. and 30 mm i.d., respectively, as shown in Fig. 2. The tip of the fuel nozzle is located 27 mm downstream from the furnace base.

The experimental conditions are listed in Table 1. The main fuel used was propane (\(C_3H_8\) 98.2 vol\%, \(C_4H_{10}\) 1.0 vol\%, and \(C_2H_4\) 0.8 vol\%), and hydrogen was used for the pilot flame. The total airflow rate was fixed at 120 l/min. Thus, the global equivalence ratio \(\phi\) was determined by the fuel flow rate. The ratio of the hydrogen flow rate to the total fuel flow rate was fixed at 0.3. The air velocity difference parameter \(\Delta U_a\) is based on each mean velocity of each air nozzle and interpreted as the turbulent effect at the flame boundary. In exposing fluid properties, a cylindrical coordinate is adopted, where the radial and axial directions are denoted by \(r\) and \(z\), respectively. The origin is set at the center of the fuel nozzle exit. Flame photographs and NOx data obtained in the previous studies \(^{(7)(8)}\) are referenced in order to facilitate the discussion of the mechanism that is influenced by the flow field. Photographs of flames were taken directly by a digital camera (OLYMPUS, 731).
Table 1 Experimental conditions for velocity measurements.

<table>
<thead>
<tr>
<th>Furnace inner diameter, ( D_1 ) [mm]</th>
<th>92</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global equivalence ratio, ( \phi )</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Total air flow rate, ( Q_{air} ) [l/min]</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Air Velocity difference, ( \Delta U_a ) [m/s]</td>
<td>8 10 12 8 14 8 14</td>
<td></td>
</tr>
<tr>
<td>High air velocity, ( U_h ) [m/s]</td>
<td>9.8 11.5 13.2 9.8 14.9 9.8 14.9</td>
<td></td>
</tr>
<tr>
<td>Low air velocity, ( U_l ) [m/s]</td>
<td>1.8 1.5 1.2 1.8 0.9 1.8 0.9</td>
<td></td>
</tr>
<tr>
<td>Measurement height, ( z ) [mm]</td>
<td>25, 50, 100, 150, 200, 250</td>
<td></td>
</tr>
</tbody>
</table>

C-5050ZOOM) with an exposure of 1/5 s and F2.3. NOx concentration measurements were performed at the exit of the furnace using an NOx-O2 gas analyzer (SHIMAZU, NOA-7000).

3. Results and Discussion

3.1 Flame appearances

Figure 3 shows instantaneous flame photographs in terms of \( \Delta U_a \) for \( \phi = 0.4 \) and \( D_1 = 95 \) mm. The increase in \( \Delta U_a \) leads to the decrease in the flame size and the enlargement of the blue flame region, which are caused by the enhancement of the mixing and the flame stretch, respectively. Figure 4 shows flame photographs in terms of \( \phi \) for \( \Delta U_a = 8 \) m/s and \( D_1 = 95 \) mm. In the present study, the total airflow rate is kept constant at 120 l/min and no additional inert gas was introduced in the fuel stream. Thus, higher values of \( \phi \) correspond to higher fuel jet velocities. The increase in \( \phi \) increases the flame size, and the flames of \( \phi = 0.6 \) and 0.8 touch the wall. The flame length is approximately proportional to \( \phi \). The values
of $\phi = 0.4, 0.6,$ and 0.8 are evaluated to have flame Reynolds numbers of 4,500, 6,800, and 9,100 based on the inner diameter of the fuel nozzle. At Reynolds numbers less than 10,000, the effect of the buoyancy on the flow field of turbulent nonpremixed flame with a coflow air cannot be neglected, as reported by Muniz and Mungal (9). However, the buoyancy effect is limited in confined flames, especially in cases in which flames fill the passage of the furnace. The buoyancy effect may be strengthened in larger furnaces. In addition, the buoyancy effect enhances the entrainment due to the acceleration of the flow. However, in the present discussion, the effect is neglected as being small in our configurations. Figure 5 shows flame photographs in terms of $D_1$ for $\Delta U_a = 8$ m/s and $\phi = 0.4$. The increase in $D_1$ causes the flame to become slender. A decrease in the main jet width is also observed for larger steps in the investigation of flows adjacent to backward-facing steps by Chen et al. (5).

3.2 Effect of Temperature on EINOx Characteristics

Based on the Zel’dovich mechanism (10), which elucidates the remarkable production of NOx at temperatures over 1,800 K, the formation of NOx in turbulent combustion can be closely related to the flame temperature. The evaluation of NOx emission is given in terms of the emission index of NOx, EINOx, which is defined by the total grams of NOx produced when 1kg of fuel was burned. The EINOx characteristics of confined nonpremixed flames investigated in previous studies (7)(8) are reviewed in Fig. 6 with the information of temperature distributions shown in Figs. 7, 8, and 9. In the cases of $D_1 = 95$ mm and in the case of $D_1 = 182$ mm for $\phi = 0.4$, the EINOx increases with $\Delta U_a$ in the lower range of $\Delta U_a$ and decreases in the higher range of $\Delta U_a$. This is related to enhanced mixing and the stretch effect, as discussed in a previous paper (8). The effect of $\Delta U_a$ on the mixing is observed in temperature distributions along the central axis shown in Fig. 7(a). In the cases of $\Delta U_a = 14$ m/s, temperature peaks are shifted further upstream than in cases of $\Delta U_a = 8$ m/s. This corresponds to the decrease in flame size caused by the enhancement of the mixing with $\Delta U_a$ (Fig. 3). Furthermore, in the cases of $D_1 = 95$ mm, the maximum temperature increases slightly. However, the effect of the flame stretch or the dilution (discussed later) is also observed at the flame base as a decrease in temperature in the reaction region at $z = 50$ mm, as shown in Fig. 8. Therefore, the decrease in the EINOx in
the range of $\Delta U_a$ above 8 m/s should be caused by the interrelation of the flame stretch and the dilution in the reaction region, and also by the decrease in flame size, which reflects a decrease in the residence time of fuel passing through the flame. In cases of $D_1 = 95$ mm, the effect of $\phi$ on the EINOx is small, as shown in Fig. 6, with a slight decrease in the EINOx. Conversely, the increase in $\phi$ leads to the increase in flame size with a slight increase in flame temperature, as shown in Figs. 4 and 7(b). Flame size is approximately proportional to $\phi$. Therefore, the effect of the residence time of the fuel on the EINOx can be neglected. Thus, the slight decrease in the EINOx should be caused by the dilution as a result of the entrainment of the burned gas of which the oxygen concentration decreases with $\phi$. Consequently, the increase in mean temperature below 1,800 K does not contribute greatly to the production of the EINOx. In the cases of $D_1 = 182$ mm, the effects of these

Fig. 8 Temperature distributions in terms of $\Delta U_a$ for $\phi = 0.8$ and $D_1 = 95$ mm.

Fig. 9 Temperature distributions in terms of $\Delta U_a$ for $\phi = 0.8$ and $D_1 = 182$ mm.
factors on the EINOx are amplified; namely, the distinct decreases in EINOx with increasing $\Delta U_a$ and $\phi$. The increase in $D_1$ leads to a decrease in temperature, as shown in Fig. 7, which is attributable to the dilution by the burned gas. The increase in $\Delta U_a$ leads to the upstream shift of the temperature peak (Fig. 7), which is attributable to the contraction of the flame size and a decrease in the temperature in the reaction region at the flame base (Fig. 9). Thus, the decrease in the EINOx is caused by the decrease in the residence time, the enhanced mixing, and the increase in the flame stretch. The increase in $\phi$ enlarges the flame by increasing the fuel flow rate, as shown in Fig. 4. In this case, the decrease in EINOx is again caused by the dilution due to the burned gas with a lower oxygen concentration.

3.3 Flow fields

3.3.1 Effect of turbulence at the flame boundary

Driscoll et al. (2) and Kim et al. (11) investigated the coaxial flow effect on the EINOx; namely, the flame stretch and the mixing. The factor $\Delta U_a$ may affect confined flames in a similar way. Figure 10 shows the radial distributions of mean axial velocity $U$ and fluctuations (rms) $u'$ in terms of $\Delta U_a$ for $\phi = 0.4$ and $D_1 = 92$ mm. In the case of $\Delta U_a = 8$ m/s, the fuel and air flows can be clearly identified at $z = 25$ mm. The turbulence is generated primarily at the boundary of the fuel jet. Conversely, in the case of $\Delta U_a = 12$ m/s, the fuel flow merges with the airflow to form a unified velocity distribution at $z = 25$ mm. The turbulence in the airflow is strengthened due to the increase in $\Delta U_a$. This should act as the flame stretch to decrease the flame temperature at the flame base, as shown in Figs. 8 and 9. Distributions of $U$ and $u'$ similar to the distribution of $\Delta U_a = 12$ m/s at $z = 25$ mm are observed in the distributions of $\Delta U_a = 8$ m/s downstream at $z = 150$ mm. At $z = 250$ mm, the distributions of $U$ and $u'$ for both cases become monotonic hilly shapes. The increase in $\Delta U_a$ also reflects the enhancement of the mixing. Another important consideration is the expansion of the region of backward flow with $\Delta U_a$. In the case of $\Delta U_a = 8$ m/s, the region was limited at $z = 100$ mm and 150 mm in our measurements. Conversely, in the case of $\Delta U_a = 12$ m/s, the backward flow is more widespread. The regions of backward flow are indicated by the negative values of $U$ and $u'$ in the figure. The dilution by the burned gas is also evident from the lower oxygen concentration in the region of backward flow.

Fig. 10 Radial distributions of mean $U$ and fluctuation (rms) $u'$ of axial velocity in terms of $\Delta U_a$ for $\phi = 0.4$ and $D_1 = 92$ mm.
\( \Delta U_a = 12 \text{ m/s} \), the region expands from \( z = 50 \text{ mm} \) to 150 mm, reflecting the enhancement of the dilution.

The increase in \( \Delta U_a \) in the airflows should affect the mixing and the flame stretch as described above. The flame stretch affects the decrease in temperature. The mixing has two influences; namely, the enhancement of reaction through the mixing of the fuel and the air, and the dilution through the entrainment of the burned gas. The former leads to the increase in temperature. Conversely, from the above result, in which the region of the backward flow is expanded with \( \Delta U_a \), the latter is strengthened for larger \( \Delta U_a \). The EINOx characteristics in terms of \( \Delta U_a \) in Fig. 6 reflect the relationship among these effects; that is, the reaction is enhanced with \( \Delta U_a \) at smaller \( \Delta U_a \) to increase the EINOx, and the flame stretch and the dilution are enhanced at larger \( \Delta U_a \) to decrease the EINOx.

### 3.3.2 Effect of global equivalence ratio

Figure 11 shows the radial distributions of \( U \) and \( u' \) in terms of the global equivalence ratio \( \phi \) at \( \Delta U_a = 8 \text{ m/s} \) and \( D_1 = 92 \text{ mm} \). Basic differences exist in terms of \( \phi \) at the flame base. The increase in \( \phi \) corresponds to the increase in the fuel flow rate. Therefore, \( \phi = 0.6 \) results in a higher velocity than \( \phi = 0.4 \) and produces stronger turbulence at the boundary of the fuel flow. Conversely, both of the velocity distributions in the environs of fuel flows are very similar. The structure of the flow field downstream also resembles each reduced velocity distribution based on each maximum velocity (not shown here). However, the region with the backward flow is expanded by the enlargement of the flame size with \( \phi \). From the above discussion, the decrease in EINOx with \( \phi \) shown in Fig. 6 should be explained by the dilution due to the burned gas. Note that the temperatures shown in Fig. 7 are less than 1,800 K. This means that the temperature increase below 1,800 K does not strongly affect the production of EINOx.

### 3.3.3 Effect of inner diameter of furnace

Figure 12 shows the radial distributions of \( U \) and \( u' \) in terms of \( D_1 \) for \( \Delta U_a = 8 \text{ m/s} \) and
\( \phi = 0.4 \). Differences between the distributions exist downstream. The increase in \( D_1 \) enhances the mixing to spread the \( U \) distribution faster and decrease the velocity in the center region. However, the velocity is reversed further downstream; that is, in the larger \( D_1 \) case, the velocity becomes faster at \( z = 250 \text{ mm} \). This phenomenon is thought to be caused by a recirculation vortex generated at the flame base. The backward flow is clearly enhanced in the case of \( D_1 = 180 \text{ mm} \) and the recirculation region is expanded, as shown by negative values of \( U \). Therefore, the recirculation vortex generates the stronger mixing at the flame base to decrease \( U \) (\( z = 100 \text{ mm} \) to \( 200 \text{ mm} \)), but delays the velocity decrease by squeezing of the flame (\( z = 250 \text{ mm} \)). This corresponds to the flame appearance, in which the flame becomes slender with increasing \( D_1 \). This mixing process is thought to be directly related to the reduction in EINOx shown in Fig. 6. Consequently, the reduction in EINOx with \( D_1 \) is caused by the dilution due to the burned gas.

### 3.3.4 Recirculation Flow Characteristics

In accordance with the evaluation of the main jet introduced by Curtet (3), who discussed the recirculation phenomena of confined cold jets, recirculation flows inside furnaces can be characterized as shown below, with consideration of the thermal expansion of flame. Each \( U \) distribution can be separated into the main jet zone and the recirculation zone. Investigation of the recirculation zone, however, is considerably difficult, because

![Fig. 12 Radial distributions of mean \( U \) and fluctuation (rms) \( u' \) of axial velocity in terms of \( D_1 \) for \( \Delta U_a = 0.8 \text{ m/s} \) and \( \phi = 0.4 \).](image)

![Fig. 13 Axial changes of volume flow rate of main jet](image)
negative values of axial velocity to identify the recirculation zone are not large. Therefore, the recirculation flow characteristics will be discussed by examining the main jet zone.

To facilitate further discussion, the parameter
\[ Q = \int_0^R 2\pi Urdr \]
which represents the volume flow rate within the main jet zone, is introduced. Here, \( R \) is the maximum radius of the main jet zone with positive axial velocities, and \( U \) is the axial velocity. Axial changes in \( Q \) are shown in Fig. 13. The flow rate \( Q \) is affected by the thermal expansion attributable to the reaction. However, the above velocity distributions clearly reflect the effects of \( \phi \), \( \Delta U_a \), and \( D_1 \). Thus, \( Q \) must indicate the entrainment process by the recirculation vortex. Curtet (3) revealed that the maximum value of \( Q \) is positioned approximately on the cross section of the core of the recirculation vortex. Then, \( Q \) increases due to the entrainment upstream of the core and decreases downstream of the core due to the excess discharge of fluid from the main jet to the recirculation vortex to maintain the confined flow stable. In cases of \( \phi = 0.4 \) and \( D_1 = 92 \text{ mm} \), the increase in \( \Delta U_a \) increases \( Q \). This is reliable evidence of the enhancement of the entrainment due to the turbulence at the flame boundary. Furthermore, this increase tends to be intensified between \( z = 50 \text{ mm} \) and \( 100 \text{ mm} \) upstream of the position of maximum \( Q \) (\( z = 150 \text{ mm} \)) with \( \Delta U_a \). In other words, the core tends to move upward with \( \Delta U_a \) even though the present results do not show the movement of the position of maximum \( Q \). The flow rates \( Q \) downstream of \( z = 200 \text{ mm} \) must reflect flow fields of the flames downstream of recirculation vortices, as shown by the different tendency of the main jet. The effect of \( \phi \) is confirmed by comparing the cases of \( \phi = 0.4 \) and \( 0.6 \) for \( \Delta U_a = 8 \text{ m/s} \) and \( D_1 = 92 \text{ mm} \). The flow rate \( Q \) tends to increase at \( z = 200 \text{ mm} \) and \( 250 \text{ mm} \) for \( \phi = 0.6 \), indicating the expansion of the recirculation vortex. The effect of \( D_1 \) is more clearly indicated in the case of \( D_1 = 180 \text{ mm} \) for \( \phi = 0.4 \) and \( \Delta U_a = 8 \text{ m/s} \). The increase in \( D_1 \) increases \( Q \) and the vortex size, while the core is not confirmed in the present result. These results reveal that the present factors \( \Delta U_a \), \( \phi \), and \( D_1 \) enhance the mixing.

Curtet (3) also pointed out that the maximum \( Q \) qualitatively reflects the flow rate entrained to the main jet. Thus, the maximum \( Q \) may be related to the parameter \( D_1 U_F \Delta U_a \), which was introduced in a previous paper (8) to express the dilution through the mixing of the burned gas and the flame stretch. Here, \( U_F \) is the exit mean velocity of the fuel. Figure 14 shows the maximum \( Q \) with respect to \( D_1 U_F \Delta U_a \). The maximum \( Q \) is approximately proportional to \( D_1 U_F \Delta U_a \). Consequently, the EINOx characteristics of confined diffusion flames are dominated by the dilution of burned gas and the flame stretch.

4. Conclusions

The flow field characteristics have been investigated in relation to the NOx properties in the configuration of jet nonpremixed flames in cylindrical furnaces as a complement to previous investigations. In particular, the effects of the air inlet velocity difference \( \Delta U_a \), the global equivalence ratio \( \phi \), and the furnace inner diameter \( D_1 \) have been examined. The obtained results are summarized as follows:
1. Recirculation vortices are generated at the base of confined nonpremixed flames. The vortices work against the entrainment of burned gas to the flames. The entrained flow rate increases with the parameters $\Delta U_a$, $\phi$, and $D_1$.

2. The NOx characteristics of confined nonpremixed flames are dominated by the mixing process, which has the effects of flame stretch, enhancement of the reaction through the mixing of fuel and air, and dilution by the burned gas. The EINOx characteristics of confined nonpremixed flames are determined based on the relationship among these effects.

3. The increase in turbulence at the flame boundary characterized by $\Delta U_a$ leads to the contraction of the flame. This is caused by the enhancement of the mixing. In cases of smaller inner diameter furnaces, the EINOx increases with $\Delta U_a$ in a range of smaller $\Delta U_a$ due to enhancement of the reaction but decreases in a range of greater $\Delta U_a$ due to flame stretch and dilution. In cases of larger inner diameter furnaces, the EINOx decreases with $\Delta U_a$ due to dilution, with the exception of case of smaller $\phi$.

4. The increase in $\phi$ leads to the enlargement of the flame. However, this also enhances the entrainment of the burned gas of lower oxygen concentration, thus decreasing the EINOx.

5. The increase in $D_1$ enlarges the recirculation vortex to enhance the dilution by the burned gas.

References


