NOx Reduction of Non-Premixed Flames by Combination of Burner and Furnaces*

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Abstract

This study proposes an idea of NOx reduction and high efficiency combustion by combination of burner and furnace. This is basically attributed to the use of entrainment of burnt gases to flame in furnace. The entrainment of burnt gases leads the dilution of flame and the recovery of heat to be exhausted. The phenomena are strongly related to the geometry of burner and furnace. The temperature, concentration, and flow field characteristics were investigated for piloted propane non-premixed flames in the cylindrical furnaces in terms of NOx emission. The effects of the furnace inner diameter, $D_1$, air inlet velocity difference, $\Delta U_a$, and global equivalence ratio, $\phi$, on NOx emission were investigated. Moreover, two kinds of materials: Pyrex glass and stainless steel were used as the furnace wall to evaluate the radiation effect through the comparison of the flame characteristics. The emission index of NOx, EINOx, decreases roughly with the increase of above parameters. This decrease is observed to be a consequence of dilution by the burnt gases and flame stretch. The dilution is attributed to the recirculation structure, which is formed at the bottom of the furnace. The flame stretch is related to the velocity difference, which is introduced by multiple air inlets. The EINOx of confined non-premixed flame is scaled by the parameter $D_1 U_F \Delta U_a$, which is proportional to $Re_c Da^{-1}$. Here, $U_F$ is the fuel velocity, $Re_c$ is the furnace Reynolds number reflecting the turbulence in the furnace, and $Da$ is the Damköhler number reflecting the flame stretch. The parameter $D_1 U_F \Delta U_a$ is related linearly to the volume flow rate entrained in to the flame. Thus, this study verified that the EINOx of confined non-premixed flame is dominated primarily from the entrainment of burnt gases by the recirculation vortex and secondarily by the turbulence at the flame boundary, which is generated by the air velocity difference. In addition, it is found that under present experimental conditions, the radiation effect on the EINOx is small and constant with respect to the parameters. Thus, this idea has a potential for practical applications.

Key words: Dilution, Furnace Combustion, Turbulent Non-Premixed Combustion, NOx Emission, Radiation

1. Introduction

Combustion technology relates directly to energy and environment problems. Oil and natural gas are estimated to be exhausted in fifty or sixty years and coal in twice the years. High efficiency combustion technologies are requested along with the development of new energy resources. On the other hand, among the gases emitted by combustion processes,
NOx is physiologically harmful to human life, and is a cause of acid rain. Non-premixed combustion, which is used in several industrial applications, suffers from a major problem on NOx emission. Because the reaction proceeds at the stoichiometric conditions, and thereby, the flame temperature may exceed 1800 K, at which point enhances the thermal NOx reactions. Therefore, several techniques have been developed to reduce NOx emission that is included multistage combustion and flue gas recirculation combustion \(^{(1, 2)}\). The evaluation of NOx emission, which is given in terms of the emission index of NOx, EINOx, of non-premixed flames based on a flamelet concept was proposed by Peters and Donnerhack \(^{(3)}\). The EINOx scaling takes flame volume and fuel flow rate in to consideration, and this means that the EINOx is proportional to the residence time of the fuel, which is passing through the flame. Driscoll et al. \(^{(4)}\) and Kim et al. \(^{(5)}\) incorporated the flame stretch effect on NOx emission in confined flames with a co-flow air stream in to a scaling law. These investigations have not only generated scaling law but have also provided insights and understanding with respect to the flame structure of non-premixed combustion. However, these investigations were conducted in cold air surroundings.

In many practical applications, combustion is performed in a confined configuration with gaseous fuel and oxidizer, which are introduced as jets. An important aspect of confined jet flows is the existence of recirculation. Therefore, the confined combustion is strongly affected by high-temperature burnt gases transported by the recirculation. This leads the dilution of fuel and oxidizer. In addition, the entrainment of burnt gases to flame leads to high efficiency combustion through the recovery of heat, and moreover, the maximum flame temperature decreases through the dilution. For round jets, the recirculation structure may lie adjacent to the nozzle exit, where a sudden expansion configuration exists. Moreover, the furnace combustion is affected by the radiation. Thus, the NOx emission characteristics should be changed from open flame.

An investigation of the EINOx characteristics of confined flames was conducted by Noda et al. \(^{(6)}\), and showed that EINOx would significantly decrease by the increasing the inner diameter of the furnace, turbulence at the flame boundary, and global equivalence ratio. This indicated that the geometric combination of burner and furnace is an important factor to reduce the NOx emission. This study attempts to lifts the results to an idea for combustion technology, and moreover, the recirculation structure and the radiation effects on the emission characteristics are investigated based on the temperature, concentration, and flow fields of the confined propane jet non-premixed flames.

### 2. Experimental Apparatus

The experimental apparatus is basically the same as that reported by Noda et al. \(^{(6)}\), the details of which are presented, and then is herein explained in terms of evaluation of radiation and measurement of flow fields. Furnaces are cylindrical and a burner is set at the center of the bottom of the furnaces. Pyrex glass and stainless steel tubes were used as furnace walls. Each set of Pyrex glass and stainless steel walls was used to evaluate the effect of radiation through the comparison of the flame characteristics. Therefore, the stainless steel cylinders were completely covered by insulators. The Pyrex glass makes penetration of thermal radiation in the range of wave length between 0.3 and 4.0 µm. This range is a part of the wave length of thermal radiation, but the main part in terms of the emissive power. Other stainless steel walls were used to measure laser Doppler velocity. Each of them has a pair of quartz windows of 600 \( \times \) 55 mm\(^2\), which has thickness of 2 mm, on the front and back sides. The cylindrical furnace walls having the inner diameter (i.d.) of 95, 142, and 182 mm were used to investigate the effects of the furnace geometry, and each furnace is 840 mm in height. The fuel nozzle is constructed of a stainless pipe of 2 mm i.d. with a rim thickness of 0.2 mm and a pilot nozzle of 3.19 mm i.d. with a rim thickness of 0.3 mm. The fuel nozzle projects 27 mm in to the furnace. Two air nozzles surround the fuel
Table 1 Experimental conditions for fuel.

<table>
<thead>
<tr>
<th>Global equivalence ratio $\phi$</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane $U_{C_3H_8}$ [m/s]</td>
<td>10.4</td>
<td>15.5</td>
<td>20.7</td>
<td>23.3</td>
</tr>
<tr>
<td>Pilot flame (H$<em>2$) $U</em>{H_2}$ [m/s]</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>9.1</td>
</tr>
<tr>
<td>Reynolds number $Re$</td>
<td>4500</td>
<td>6800</td>
<td>9100</td>
<td>10200</td>
</tr>
</tbody>
</table>

Table 2 Experimental conditions for airflows.

<table>
<thead>
<tr>
<th>Total airflow rate $Q_a$ [l/min]</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity difference $\Delta U_a$ [m/s]</td>
<td>2</td>
</tr>
<tr>
<td>High air velocity $U_H$ [m/s]</td>
<td>4.7</td>
</tr>
<tr>
<td>Low air velocity $U_L$ [m/s]</td>
<td>2.7</td>
</tr>
</tbody>
</table>

nozzle at the bottom of the furnace. The inner and outer nozzles are of higher and lower velocity, respectively. The higher-velocity nozzle is of 12 mm i.d. with a rim thickness of 1 mm, and the lower-velocity nozzle is of 30 mm i.d. with a rim thickness of 1 mm.

Propane ($C_3H_8$ 98.2 vol%, $C_4H_{10}$ 1.0 vol%, and $C_2H_4$ 0.8 vol%) was used as the main-fuel, and hydrogen was used as the pilot-flame. The volumetric ratio of the hydrogen flow rate to the total-fuel flow rate was fixed at 0.3, nevertheless the ratio of the heat-release of the hydrogen flow rate to the total-heat-release rate is approximately 4.8%. The air velocity difference, $\Delta U_a$, is based on the difference between high-velocity air, $U_H$, and low-velocity air $U_L$. The parameter, $\Delta U_a$, is interpreted as the turbulent intensity at the flame boundary. Here, the total airflow rate was fixed to 120 l/min. Thus, the increase in the fuel velocity, $U_f$, increases the global equivalence ratio, $\phi$.

Velocity measurements were implemented using a laser Doppler velocimetry (LDV) system (TSI, IFA 755) with the equipment error of 0.1%. Magnesium oxide powder of 1 µm in mean diameter was used as the particle tracker. The fluctuation of gas density refracts the laser beams to shift the measurement point and change the measurement area. Based on Yanagi (7), in the evaluation, the velocity measurement errors were less than 2%.

Concentration measurements were performed using a NOx-O$_2$ gas analyzer (SHIMAZU, NOA-7000) for NOx (NO and NO$_2$), and an infrared gas analyzer (SHIMAZU, CGT-7000) for CO and O$_2$. Moreover, a preprocessing unit, referred to as a gas sampling unit (SHIMAZU, CFP-8000), was used to remove particles such as water and soot. A sampling probe of 2 mm i.d. was cooled by water in order to freeze the reaction and withstand the high temperatures. The sampling line between the probe and the analyzer however was heated to over 100°C in order to avoid condensation of H$_2$O. NOx data is discussed only for the flame condition in which the CO concentration is lower than 300 ppm. The temperature was measured by a Pt/Pt-13%Rh thermocouple of 0.1 mm coated with Y$_2$O$_3$-BeO in order to avoid catalysis. Flame photographs were taken with a digital camera (OLYMPUS, C-5050ZOOM) with an exposure of 1/5 s and F2.3. The experimental conditions are given in Table 1 and 2. The coordinates $z$ and $r$ used below are of the axial and radial directions, respectively. In this paper, a limited number of data are presented in order to facilitate discussion and because of the space limitation.

3. Results and Discussion

3.1 Flame appearances

Figure 1 shows flames in Pyrex wall furnaces with respect to furnace inner diameter, $D_1$, and air velocity difference, $\Delta U_a$, for a global equivalence ratio $\phi = 0.8$. The increase in $D_1$ leads to the contraction of the luminous flame region, and the expansion of the blue flame region. This tendency is enhanced by $\Delta U_a$. In the case of $D_1 = 182$ mm, the luminous flame region vanishes at $\Delta U_a = 12$ and 14 m/s. The increase in the $\Delta U_a$ decreases the flame length, with a linear decrease in the luminous region, and with a linear increase in the blue flame region. The flame appearances with respect to $D_1$ and $\Delta U_a$ may be related to the enhancement of mixing at the flame base and the flame stretch. Recirculation vortices,
which should be generated around the furnace base, may play an important role in mixing in furnace combustion \(^{(6)}\). The flame stretch acts to cool the flame.

### 3.2 Entrainment characteristics

The flame characteristics of confined flames should be strongly affected by the dilution process through recirculation vortices. Therefore, a qualitative parameter is required to express the dilution level. Figure 2 shows axial velocity and its fluctuation distributions of case of \( D_1 = 95 \) and 182 mm for \( \Delta U_a = 14 \) m/s and \( \phi = 0.8 \). An important point is negative velocities around jet to show the existence of recirculation vortices. In the case of \( D_1 = 95 \) mm, the negative velocities exist until \( z = 100 \) mm. On the other hand, in the case of \( D_1 = 182 \) mm, the negative velocities exist beyond \( z = 250 \) mm, and the maximum value is larger than the case of \( D_1 = 95 \) mm. This means that the recirculation vortex becomes larger and stronger with the increase of \( D_1 \). Thus, the velocities of the case of \( D_1 = 182 \) mm of the center jet at \( z = 250 \) mm are larger than of the case of \( D_1 = 95 \) mm. This is an evidence of the enhancement of the entrainment. The flow fields can be separated in to a jet zone and a recirculation zone by the positive and negative signs, respectively, of the mean velocity \(^{(8)}\).

The recirculation flow characteristics are here discussed by examining the jet zone. To facilitate further discussion, a parameter that represents the volumetric flow rate within the jet zone, \( Q \), is introduced:

\[
Q = 2\pi \int_{0}^{R} U r dr
\]

where \( R \) is the maximum radius of the jet zone. The integration is defined only for axial
velocity. Thus, $Q$ approximately indicates the entrainment process by the recirculation vortex. Axial distributions of $Q$ from experimental data are shown in Fig. 3. The maximum value of $Q$ is positioned approximately on the cross section of the core of the recirculation vortex. The $Q$ increases in the upstream region of the recirculation vortex because of the entrainment process, and decreases in the downstream region of the vortex because of the discharge of gases from the jet zone to recirculation zone to keep the confined flow stable. Therefore, the peak is approximately located on the cross section of the core of the recirculation vortex. In the case of $D_1 = 95$ mm in Fig. 3, the increase in $\Delta U_a$ enhances the entrainment process and leads to a higher peak value. The increase in $\phi$ slightly increases $Q$ at $z = 200$ and 250 mm, with approximately the same peak value as in the case of $\phi = 0.4$. In the case of $D_1 = 182$ mm, $Q$ increases and extends downstream region. This implies that the entrainment process is enhanced and sustained in a broader space in the furnace with $D_1$.

Each maximum value of $Q$ in Fig. 3 is denoted as $Q_{\text{max}}$, and may qualitatively indicate the amount of burnt gases entrained in to the jet zone. Noda et al. introduced a parameter $D_1 U_F \Delta U_a$, that is proportional to $Re_c Da^{-1}$ to scale the EINOx of confined non-premixed flames. Here, the furnace Reynolds number $Re_c = D_1 U_F / \nu$ is based on the furnace inner diameter, which reflects the turbulence in the furnace, i.e. the dilution. The furnace Reynolds number is an analogue to the backward-step flows, of which flow structures are dominated by the step-height and the main flow velocity. The Damköhler number, $Da$, is related to the air velocity difference; the number which is inversely proportional to the stretch rate $S = \Delta U_a / \Delta L$, where $\Delta L$ is the distance between the two air nozzles. Noda et al. found that the EINOx characteristics are proportional to the parameter $D_1 U_F \Delta U_a$ with a negative factor for propane flames. Figure 4 shows $Q_{\text{max}}$ as a function of $D_1 U_F \Delta U_a$. The $Q_{\text{max}}$ increases linearly with respect to $D_1 U_F \Delta U_a$. Consequently, the EINOx of confined non-premixed flames is determined primarily from the entrainment of burnt gases by the recirculation vortex and secondarily by the turbulence at the flame boundary, which is generated by the air velocity difference.

![Fig. 3 Axial distributions of jet volume flow rate evaluated from velocity data.](image)

![Fig. 4 $Q_{\text{max}}$ as a function of $D_1 U_F \Delta U_a$.](image)
3.3 Effects of $D_1$ on temperature and oxygen concentration

Figure 5 shows changes in temperature with respect to the inner diameter of the furnace for the case of $\phi = 0.8$ and $\Delta U_a = 14$ m/s in Pyrex glass wall furnaces. The temperature radial distributions at $z = 50$ mm show the maximum values in the flame regions identified by the blue flame in Fig. 1. The temperature decreases outside the high temperature region because of the cooling caused by the airflow. However, the temperature again increases outside the airflow. This is possibly caused by the transportation of the burnt gases towards the upstream region by recirculation vortex. The increase in $D_1$ decreases the temperature in the flame region. This is caused by the dilution through the strengthened burnt gases self-recirculation (BGSR), resulting from the enlarged vortices. On the other hand, the maximum temperatures near $r = 20$ mm do not change monotonically with $D_1$. This is attributed to the vortex strength and the temperature of burnt gases. In the case of $D_1 = 95$ mm, the strength of the vortex is weaker, and thus the temperature characteristics should be dominated by the cooling, which is caused by the cold air flow. The increase in $D_1$ enhances the effects of BGSR and increases the ambient temperature in the case of $D_1 = 143$ mm. However, the BGSR also decreases the flame temperature, and consequently, the temperature of burnt gases. This causes a decrease in the ambient maximum temperature at near $r = 20$ mm in the case of $D_1 = 182$ mm. The temperature profiles at $z = 150$ mm and 250 mm may reflect the above flame appearances with respect to the luminosity and flame size. The temperature distributions tend toward uniform with $D_1$.

Figure 6 shows the radial distribution of oxygen concentration for the case of $D_1 = 95$ and 182 mm for $\phi = 0.8$ and $\Delta U_a = 14$ m/s in Pyrex glass wall furnaces. The distributions of $O_2$ concentration at $z = 50$ mm show a saddle-shape, which is attributed to the air supplies. The increase in $D_1$ decreases the concentration in the flame and the ambient regions because
of the dilution. Note that the concentration near the wall from $z = 50$ to 250 mm is maintained approximately 5 vol% for the case of $D_1 = 182$ mm. This is an evidence of the occurrence of BGSR. The dilution, which is attributed to BGSR, is a key factor in controlling the flame characteristics in the furnace.

### 3.4 Effect of radiation on NOx emission characteristics

Figure 7 shows emission indices of NOx (EINOx) in terms of $D_1$ for the cases of Pyrex glass and stainless steel wall, respectively. Figure 8 shows temperature distributions along the center axis in Pyrex glass and stainless steel wall furnaces for $\Delta U_a = 8$ m/s, respectively. The EINOx difference for both furnaces is attributed to the radiation with the consideration of the penetration wave length of Pyrex glass mentioned above. The characteristics of EINOx may be related to the above flame appearances, i.e. the EINOx is roughly proportional to the luminosity. The increase in $D_1$, $\Delta U_a$, and $\phi$ decreases EINOx with exceptions of $\Delta U_a$ and $\phi$ for $D_1 = 95$ mm. The increase in $D_1$ enlarges the recirculation vortices as described above, thereby enhances the entrainment of burnt gases, and hence dilution. The increase in $\Delta U_a$ for the lower range in the case of $D_1 = 95$ mm increases the EINOx as a result of the enhancement of the reaction through the mixing of fuel and oxidizer. However, the larger $\Delta U_a$ decreases the EINOx, and this is caused by the flame...
cooling associated with flame stretch and the dilution through the more enhancement of mixing. The increase in $\phi$ increases the furnace Reynolds number, $Re_c = D_1 U_F / \nu$, under the present conditions, reflecting the turbulent intensity in the furnace as mentioned above. Thus, the increase also works for the enhancement of dilution through the recirculation of the burnt gases of lower oxygen concentration. Moreover, the increase in $\phi$ for $D_1 = 182$ mm increases non-linearly the flame volume and the increase rate is depressed with $\phi$ \(^{(6)}\). This leads to the decrease in EINOx, which is defined as the total grams of NOx produced per 1 kg of fuel burnt. Then, the above exception is elucidated with the temperature distributions in Fig. 8 (a). In the case of $D_1 = 95$ mm, sizes of recirculation vortices are smaller, and thereby, the dilution effect is weaker. The volume of the flame and total heat amount become larger with $\phi$, and the maximum temperature becomes higher as shown in Fig. 8 (a). This leads to the increase in EINOx. This tendency is stronger for the adiabatic case of steel wall. Thus, the radiation effect on the EINOx becomes stronger. The EINOx difference between the Pyrex and steel walls changes from approximately 0.1 g/ (kg fuel) for $\phi = 0.4$ to 0.5 for $\phi = 0.6$ in the case of $D_1 = 95$ mm. However, in the case of $D_1 = 182$ mm, the EINOx difference changes from approximately 0.1 g/ (kg fuel) for $\phi = 0.4$ to 0.4 for $\phi = 0.6$ and 0.8. The negligible differences between the $D_1 = 95$ mm and 182 mm for $\phi = 0.4$ is caused by smaller volumes of the flames. The decrease in the EINOx differences for the larger $\phi$ of 0.6 and 0.8 in the case of $D_1 = 182$ mm is also caused by the reduction of the flame volume due to the dilution as shown in Fig. 1. This volume reduction weakens the
radiation effect. The dilution effect enhanced in $D_1 = 182 \text{ mm}$ depresses maximum temperature. The increase in $\phi$ for $D_1 = 182 \text{ mm}$ does not lead to an increase in maximum temperature through the entrainment of burnt gases with lower oxygen concentration. Thereby, the radiation effect is decreased for larger $\phi$ in the case of $D_1 = 182 \text{ mm}$. Figure 9 shows the radiation effect on EINOx with respect to the parameter $D_1U_F\Delta U_a$, and the EINOx decreases linearly with the parameter, and the radiation effect is approximately constant except for small values of the parameter. Considering the reaction rate of NOx, as an exponential function of temperature, these results reflect small temperature changes furnace can reduce the NOx emission, even though flames are exposed to radiation. The finding is derived from simple and fundamental experiments; thus, this idea of NOx reduction by the combination of burner and furnace should be explored in practical burners like swirl burners in near future.

4. Conclusions

This study investigates the NOx characteristics of confined non-premixed flames in order to verify an idea of the NOx reduction by the combination of burner and furnace. In this study, NOx reduction is relied on the dilution by burnt gases entrained to flame. The dilution is attributed to recirculation structure, which is formed at the bottom of furnace. The entrainment of burnt gases by recirculation vortices is well known; nevertheless the idea of the combination of the burner and furnace in terms of NOx reduction is not in general. To quantify the entrainment, a parameter that represents the volumetric flow rate within the jet zone, $Q$, has been introduced. Experimentally, it has been found that the maximum volume flow rate of $Q$ is linearly related to a parameter $D_1U_F\Delta U_a$, where $D_1$ is the inner diameter of furnace, $U_F$ is the fuel velocity, and $\Delta U_a$ is the velocity difference between high and low air velocities. The parameter $D_1U_F\Delta U_a$, which is proposed by Noda et al. (6), is proportional to $Re_cDa^{1/2}$. Here, $Re_c$ is the furnace Reynolds number, and $Da$ is the Damköhler number. The Damköhler number is inversely proportional to the stretch rate. In addition, the parameter can entirely scale the NOx emission characteristics in terms of EINOx, which decreases linearly with the parameter. Thus, this study verified that EINOx of confined non-premixed flames is dominated primarily from entrainment of burnt gases by the recirculation vortex, and secondarily by the turbulence at the flame boundary, which is generated by the air velocity difference. Moreover, the radiation effect on the NOx emission investigated through the comparison of NOx characteristics between Pyrex glass and stainless steel wall furnaces. The radiation effect under the present conditions is small, and the EINOx difference is almost constant with respect to $D_1U_F\Delta U_a$. Thus, this result verified that the idea of the NOx reduction by the combination of burner and furnace can apply to practical equipment.

References


