An Experimental Study of Flame Characteristics of Jet Diffusion Flames in Cylindrical Furnaces*

(1st Report, Effect of Inner Diameter of Furnace on NOx Emission Properties)

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Abstract

The combination of a burner and a combustion chamber is an important factor controlling flame characteristics. However, to our knowledge, this factor has yet to be investigated systematically. In the present study, coaxial jet diffusion flames in cylindrical combustion chambers have been studied in terms of inner diameters of the combustion chambers, global equivalence ratios, and turbulence in airflow. A fuel nozzle is composed of a stainless steel tube having an inner diameter (i.d.) of 2 mm with a coaxial pilot burner of 3.19 mm i.d., surrounded by two air coaxial tubes of 12 mm i.d. and 30 mm i.d., respectively. The inner and outer air tubes are for higher and lower airflows, respectively, and the turbulence in the airflow is changed by the velocity difference. The main fuel is propane. Hydrogen is used for the pilot flame, with a volumetric fuel ratio of 0.3. Each wall of the combustion chamber is made of a heat-resistant glass Pyrex tube so that each flame can be visualized. The inner diameter of the furnace is varied in order to investigate the effect of furnace size on the flame characteristics. The increase in the diameter of the combustion chamber has been found to enhance the exhaust gas self-recirculation, because the NOx emission decreases. The increase in turbulence in the airflow strengthens the entrainment of the exhaust gas transported upstream by the recirculation vortex. The increase in the global equivalence ratio from 0.2 to 0.8 in the present study decreases the oxygen concentration of the exhaust gas and leads to diluted combustion through the exhaust gas self-recirculation. A proper combination of these factors has been found to yield a low NOx combustion.

Key words: Turbulent Diffusion Flame, Combustion Chamber, Exhaust Gas Recirculation, Chamber Size, Global Equivalence Ratio, Turbulence

1. Introduction

The reduction in pollutants generated through combustion processes is urgent. NOx and CO2 are global contaminations. NO and NO2 cause not only physiological harm but also acid rain. In addition, the production of CO2 during fossil combustion cannot be avoided, and so high-efficiency combustion is required.
The utilization of exhaust gas recirculation (EGR) in combustion systems facilitates both the efficient use of energy and the reduction of harmful substances. The EGR in engine systems mixes part of the exhaust gas and the air as an oxidizer to realize high-efficiency combustion and low NOx combustion (1). Swirl flows and flows behind bluff bodies used to stabilize flames are known to have the effect of EGR (2)(3). Furthermore, flameless combustion, which is realized in preheated air combustion over air temperatures of 1,300 K, expands the combustible range to allow extremely diluted combustion. Consequently, low NOx and CO2 combustion is realized (4). The EGR is a key to establish environmentally friendly combustion systems and the above conventional technologies have been explored mainly in terms of burner geometry. However, the combination of burner and combustion chamber for the furnace combustion is an important factor controlling flame characteristics, because the EGR occurs effectively in furnaces. A radiant tube burner stabilizing a flame in a small space is typical, and an appropriate combination must exist in order to utilize the EGR.

To our knowledge, the combination of burner and combustion chamber has never been investigated systematically. This may be because confined flames are not easily measured, and the dimensions of the furnace cannot be changed easily. In the present study, we develop an experimental apparatus that can easily change the dimensions of the furnace and examine the effect of the inner diameter of the furnace on the flame characteristics of confined jet diffusion flames.

2. Experimental

2.1 Experimental apparatus

Figures 1 and 2 show schematic diagrams of a burner and a cylindrical furnace, respectively. The experimental apparatus was installed vertically. The burner consists of a fuel nozzle with two air coaxial nozzles. The fuel nozzle is made of a stainless pipe having an inner diameter (i.d.) of 2 mm with a rim thickness of 0.2 mm. A pilot nozzle of 3.19 mm i.d. with a rim thickness of 0.3 mm is installed coaxially with respect to the fuel burner. Air nozzles consist of an inner higher-velocity nozzle and an outer lower-velocity nozzle, which are also installed coaxially to the fuel nozzle and are constructed of stainless steel pipe. The higher-velocity air 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. The air nozzles allow the turbulence at the flame boundary to vary with respect to the air velocity difference. The tip of the fuel nozzle is located 27 mm downstream from the furnace base, where the air nozzle exits are located. This configuration ensures interaction between the flame and the turbulence generated by the airflows.
The side wall of the furnace is made of a cylindrical Pyrex tube in order to allow the flame to be viewed. In addition, the side wall can easily be replaced in order to vary the wall size to have an inner diameter of \( D_1 = 95 \) mm (rim thickness: 2.5 mm), 142 mm (3.5 mm), or 182 mm (4.0 mm). Each glass tube was installed between lower and upper flanges. The height of the furnace is 840 mm. The present evaluation of the emission index of NOx (EINOx) is based on the NOx data at the center of the furnace exit and the fuel flow rate. Thus the uniform distribution of NOx at the exit is essential. The exit is therefore contracted to 38 mm in order to ensure a uniform concentration field. Furthermore, we compared data for the exit inner diameter of \( D_2 = 38 \) mm and for each exit inner diameter with a ratio of \( D_2/D_1 = 0.4 \) to confirm negligible differences. For measurements inside furnaces, the upper flange was removed.

### 2.2 Experimental method

The combustion characteristics of confined flames have been investigated in terms of the inner diameter of the furnace \( D_1 \), the global equivalence ratio \( \phi \), and the air velocity difference \( \Delta U/a \). Direct photography, measurements of NOx at the furnace exit, and measurements of CO, CH4, O2, and temperature in the furnaces were implemented. The NOx data was processed to EINOx in order to discuss the flame structure. The global equivalence ratio \( \phi \) is defined as

\[
\phi = \frac{F}{A} / \phi_{st},
\]

where \( F \) and \( A \) are the masses of fuel and air, respectively. The numerator is based on the supplied mass flows, and the subscript \( st \) refers to the stoichiometric condition.

Photographs of flames were taken directly by a digital camera (OLYMPUS, C-5050ZOOM) with an exposure of 1/5 s and an F2.3 lens. Concentration measurements were performed using an NOx-O2 gas analyzer (SHIMAZU, NOA-7000) for NOx (NO and NO2) and an infrared gas analyzer (SHIMAZU, CGT-7000) for CO, O2, and CH4. 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 H2O. In the present study, 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 Platinum/Platinum-13%Rodium thermocouple of 0.1 mm coated by Y2O3-BeO to avoid catalysis. Moreover, the thermocouple support, except for the measuring part, was cooled by water to protect against heat damage.

### 2.3 Experimental conditions

The experimental conditions are given in Tables 1 and 2. Propane (C3H8 98.2 vol%) was used as fuel. The fuel of the pilot flame is hydrogen, and the oxidizer is air. The total airflow rate was fixed at 120 l/min. Thus, the global equivalence ratio \( \phi \) is determined by the fuel flow rate. A larger \( \phi \) indicates a higher velocity of the fuel flow. The flow rate of the

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<th>Table 1 Experimental conditions for global equivalence ratio</th>
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<td>Global equivalence ratio ( \phi )</td>
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<td>( U_{C3H8} ) [m/s]</td>
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<td>( U_{H2} ) [m/s]</td>
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<td>Re</td>
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<th>Table 2 Experimental conditions for air velocity difference</th>
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<td>Air velocity difference ( \Delta U/a ) [m/s]</td>
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<td>High air velocity ( U_h ) [m/s]</td>
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<td>Low air velocity ( U_l ) [m/s]</td>
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hydrogen as the fuel of the pilot flame was determined on the basis of the ratio of the hydrogen flow rate \( Q_{H_2} \) to the total fuel flow rate \( Q_f \), being \( Q_{H_2}/Q_f = 0.3 \). The air velocity difference \( \Delta U_a \) is based on both the mean velocities of the higher-velocity and lower-velocity air flows and reflects the turbulence intensity at the flame boundary. The Reynolds number \( Re \) in Table 1 is based on the fuel mean velocity and the inner diameter of the fuel nozzle. All data is for CO concentrations lower than 300 ppm.

3. Results and discussion

3.1 Direct observation of flames

Figure 3 shows photographs of flames with respect to the inner diameter of the furnace \( D_1 \), the global equivalence ratio \( \phi \), and the air velocity difference \( \Delta U_a \). The increase in \( D_1 \) leads to the contraction of luminous flame region and an expansion of the blue flame region. This tendency is enhanced by \( \phi \) and \( \Delta U_a \). In particular, in the case of \( \phi = 0.8 \) and \( D_1 = 182 \) mm, the luminous flame region vanishes at \( \Delta U_a = 12 \) m/s and 14 m/s. The flame size increases with \( \phi \) because of the increase in the fuel flow rate at the fixed total airflow. In the case of \( D_1 = 95 \) mm, the flame touches the wall with an increase in luminosity that is attributable to the increase in \( \phi \). On the other hand, in the case of \( D_1 = 182 \) mm, the increase in \( \phi \) decreases the luminosity, but increases the flame size. The increase in \( \Delta U_a \) shows a decrease in the flame length, being attributable to the contraction of the luminous region.

The above flame appearances with respect to \( D_1 \), \( \phi \), and \( \Delta U_a \) may be related to the enhancement of mixing at the flame base and as a result of the change in the composition of the mixture. Recirculation vortices, which should be generated around the furnace base, may play an important role in the mixing in the furnace combustion \(^5\). Thus, the increase in

![Fig. 3 Photographs of flames](image-url)
$D_1$ leads to an increase in the size of each vortex and the exhaust gas recirculation. The increase in $\phi$ enhances the mixing because of the increase in the initial fuel velocity, as a result of $Re$ being increased, and leads to a decrease in the concentration of $O_2$ in the exhaust gas under the present experimental conditions. The increase in $\Delta U_a$ induces turbulence at the flame boundary and thus increases the flame surface area because of the increased flame stretch, leading to the contraction of flame size, and enhances the mixing with the exhaust gas, leading to lean combustion. The contraction of the luminous flame region and the enlargement of the blue flame region reflect the occurrence of lean combustion.

### 3.2 Characteristics of NOx emission

Figure 4 shows the emission indices of NOx (EINOx) based on NOx measurements at the exits of furnaces. The increase in $D_1$ decreases EINOx. This may be related to the enlargement of vortices with $D_1$. Larger vortices enhance the transport of the exhaust gas toward the upstream region to dilute the flame. Consequently, the lower temperature, based on the dilution, leads to the lower EINOx. The increase in $\phi$ also decreases EINOx. This tendency is enhanced with $D_1$. This indicates the synergistic effect of $\phi$ and $D_1$: the effect of $\phi$ to decrease the oxygen concentration under the present experimental conditions is enhanced by the larger vortices, which dilute the flames. With respect to $\Delta U_a$, there may exist two effects, because $\Delta U_a$ increases EINOx for lower $\Delta U_a$ ($< 5 \sim 8 \text{ m/s}$), but decreases EINOx for higher values of $\Delta U_a$. This tendency is stronger in the case of $D_1 = 95$ mm. These phenomena should reflect the enhancement of mixing and flame stretch \(^{(6)}\). In the case of $D_1 = 95$ mm, the size of the recirculation vortex should be smaller than the other cases, owing to the smaller space between the flames and the wall. Thus, the effect of the EGR is weakened. Therefore, the EINOx characteristics should be dominated by the interaction between the fuel and the air flows. The increase in $\Delta U_a$ enhances the mixing and activates the reaction to increase the temperature. Thus, EINOx increases. On the other hand, values of $\Delta U_a$ over 8 m/s induce the flame stretch to decrease the temperature. As a result, EINOx decreases. The above NOx characteristics are also observed in the cases of $\phi = 0.4$ for $D_1 = 143$ and 182 mm. This is caused by the sufficient oxygen to fuel ratio: $\Delta U_a$ enhances the mixing of fuel and air, as well as the reaction. Furthermore, in the case of $D_1 = 182$ mm, the incomplete combustion defined at the CO concentration of 300 ppm occurs at relatively lower $\Delta U_a$ (maximum value for each $\phi$ in Fig. 4(c)). This should be caused by the excess effects of the dilution by EGR and flame stretch.

![Fig.4 EINOx as a function of the air velocity difference](image-url)
3.3 Temperature characteristics in furnaces

Figure 5 shows changes in temperature with respect to the inner diameter of the furnace in the case of $\phi = 0.8$ and $\Delta U/a = 14 \text{ m/s}$. The temperature distributions at $z = 50 \text{ mm}$ show the maximum values in the flame regions shown in photographs in Fig. 3. The temperature decreases outside the high temperature region because of the airflow. However, the temperature again increases outside the airflow. This is thought to be caused by the transportation of the exhaust gas toward the upstream region by recirculation vortices. A gradual decrease in the temperature in the ambient region is caused by the heat loss through the heat conduction of the Pyrex wall. The increase in $D_1$ decreases the temperature in the flame region. This also is caused by the dilution through the strengthened EGR by enlarged vortices. On the other hand, the maximum temperatures near $r = 20 \text{ mm}$ do not change monotonously with $D_1$. This is attributable to the vortex strength and the temperature of the exhaust gas. In the case of $D_1 = 95 \text{ mm}$, the strength of the vortex is weaker and the temperature characteristics should be dominated by the cooling of the cold airflows. On the other hand, the increase in $D_1$ enhances the effect of the EGR and increases the ambient temperature in the case of $D_1 = 143 \text{ mm}$. However, the EGR also has the effect of decreasing the flame temperature and, consequently, the temperature of the burned gas. This causes the decrease in the ambient maximum temperature around $r = 20 \text{ mm}$ in the case of $D_1 = 182 \text{ mm}$.

The effect of $\Delta U/a$ on temperature is very similar to that on NOx emission characteristics. The increase in $\Delta U/a$ leads to a decrease in the temperature in the flame region and an increase in temperature in the ambient region (not shown here). The decrease in the temperature is caused by the enhanced flame stretch and the enhancement of mixing, which leads to dilution. The increase in temperature in the ambient region is caused by the enhanced EGR.

![Fig.5 Mean temperature profiles ($\phi = 0.8$, $\Delta U/a = 14 \text{ m/s}$)](image)

![Fig.6 CO concentration profiles ($\phi = 0.8$, $\Delta U/a = 14 \text{ m/s}$)](image)
3.4 Concentration characteristics in furnaces

Figures 6, 7, and 8 show the concentration distributions of CO, O₂, and CH₄ in the case of \( \phi = 0.8 \) and \( \Delta U_a = 14 \text{ m/s} \). The CO concentration increases in the flames. This is caused by the diffusion of CO toward the flame center, where CO is produced mainly on the rich side of the reaction zone (7). The increase in \( D_1 \) however decreases the CO concentration in the flame and increases the CO concentration in the ambient region. This reflects an increase in the amount of burned gas transported by recirculation vortices. Thus, the decrease in the CO concentration in the flame is caused by the dilution. At cross-sections of \( z = 150 \) and 250 mm, the CO concentration increases in the flame region. In the case of \( D_1 = 95 \text{ mm} \), the flame region corresponds to the luminous region, and CO is produced largely in this region. Here, as a maximum scale in Fig. 6, \( 1 \times 10^4 \) ppm indicates the upper measurement limit of the analyzer. In the case of \( D_1 = 182 \text{ mm} \), because of the dilution, the rate of increase is smaller than that in the case of \( D_1 = 95 \text{ mm} \). The CO values near the wall in the case of \( D_1 = 95 \text{ mm} \) vary greatly, but are smaller in the case of \( D_1 = 182 \text{ mm} \). This indicates the conservation of CO concentration in the recirculation vortex strengthen in the case of \( D_1 = 182 \text{ mm} \) and indirectly reflects the existence of the vortex. In the downstream region from \( z = 250 \text{ mm} \), the CO concentration decreases rapidly and becomes less than 300 ppm at the exit.

The distributions of O₂ concentration at \( z = 50 \text{ mm} \) show a saddle-shape distribution attributable to the air supplies. The increase in \( D_1 \) decreases the concentration because of the dilution. However, this tendency is reversed downstream. This is also caused by the dilution, because the dilution depresses the reaction to decrease the consumption of the air. The depression in the reaction can be justified by the decrease in temperature with \( D_1 \) shown in Fig. 5. The O₂ concentration in the case of \( D_1 = 182 \text{ mm} \) is also conserved over a large
ambient region between the flame and the wall, as in CO distributions, being attributable to the existence of a vortex.

The distributions of the CH₄ concentration are chevron-shaped around the center of the flame to \( z = 250 \text{ mm} \), but the peaks decrease rapidly with the axial distance. This indicates that CH₄ produced in the rich region on the early stage of reaction processes is consumed rapidly to change CH₃, H₂O, and so on \(^{(8)}\). The chevron-shape distributions are based on the diffusion of CH₄ toward the center of the flame. The CH₄ concentration decreases with \( D_1 \) downstream of \( z = 150 \text{ mm} \) because of the dilution. The CH₄ concentration outside of the flame region at \( z = 50 \text{ mm} \) is small (approximately 110 ppm). This value should correspond to small values downstream. The CH₄ distribution at \( z = 50 \text{ mm} \) resembles the CO distribution at the same section but the CH₄ values in the ambient region are approximately one tenth of CO values. This indicates that the scalar characteristics, such as the temperature and the concentrations between the flame and the wall, are caused by the transportation of burned gas by recirculation vortices.

4. Conclusions

Considering the reduction of pollutants, the combination of burner and furnace has been investigated with respect to jet diffusion flames in the configuration of cylindrical furnaces, especially in terms of the inner diameter of furnace \( D_1 \), the global equivalence ratio \( \phi \), and the air velocity difference between high and low velocities \( \Delta U_a \). The following results were obtained:

1. The increase in \( D_1 \) leads to the contraction of the luminous flame region and the expansion of blue flame region. The increases in \( \phi \) (\( \phi = 0.4 \) to 0.8 in the present experiments) and \( \Delta U_a \) enhance the above-described effect of \( D_1 \).
2. The increase in \( D_1 \) leads to the decrease in the flame temperature. This should be elucidated by the enlargement of recirculation vortices generated between the flame and the wall. The increase in the vortex scale with \( D_1 \) enhances the EGR to dilute the flame.
3. The increase in \( D_1 \) decreases the emission index of NOx (EINOx). This is also based on the enlargement of the vortices. These vortices transport the burned gas upstream and entrain it to the flame to be diluted. This leads to a decrease in the EINOx. The increases in \( \phi \) and \( \Delta U_a \) also decrease the EINOx. The increase in \( \phi \) causes a decrease in O₂ concentration in the burned gas, enhancing the effect of the dilution. The increase in \( \phi \) stimulates the turbulent mixing at the flame boundary to enhance the dilution.
4. The increase in \( D_1 \) suppresses a change in concentration near the wall, which reflects the conservation of the composition characteristics in the recirculation vortex.
5. Species concentration decreases with \( D_1 \). This is caused by the dilution enhanced by the enlargement of recirculation vortices.
6. The flammable range of confined flames is narrowed with \( D_1 \) owing to the dilution. This requires an appropriate combination of \( D_1 \), \( \phi \), and \( \Delta U_a \).

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References


