Characteristics of NO_X Emission with Flue Gas Dilution in Air and Fuel Sides

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Flue gas recirculation (FGR) is a method widely adopted to control NO_X in combustion system. The recirculated flue gas decreases flame temperature and reaction rate, resulting in the decrease in thermal NO production. Recently, it has been demonstrated that the recirculated flue gas in fuel stream, that is, the fuel induced recirculation (FIR), could enhance a much improved reduction in NO_X per unit mass of recirculated gas, as compared to the conventional FGR in air. In the present study, the effect of FGR/FIR methods on NO_X reduction in turbulent swirl flames by using N_2 and CO_2 as diluent gases to simulate flue gases. Results show that CO_2 dilution is more effective in NO reduction because of large temperature drop due to the larger specific heat of CO_2 compared to N_2 and FIR is more effective to reduce NO emission than FGR when the same recirculation ratio of dilution gas is used.

Key Words : Flue Gas Recirculation (FGR), Fuel Induced Recirculation (FIR), Nitric Oxides

1. Introduction

Combustion efficiency and clean combustion are the two key issues in recent fossil energy utilization. Control of nitrogen oxides (NO_X) has been a major issue in designing combustion systems, since NO_X play a key role in ozone depletion and the generation of photochemical smog (Ahn et al., 2002 ; Cho et al., 2003). Due to the temperature sensitive NO_X production mechanism, decreasing flame temperature is a viable method in suppressing thermal NO_X formation.

Lean homogeneous combustion, low oxygen combustion and other inert gas dilution are practical methods to reduce flame temperature (Wunning, 1997 ; Milani and Saponaro, 2001). Especially, flue gas recirculation (FGR) is one of the well-known methods to control NO_X emission (Beer, 1996 ; Baltasar et al., 1997 ; Arai, 2000). A portion of exhaust gases is recirculated in oxidizer (air) side in FGR, which decreases flame temperature and reduces NO_X emission, since combustion takes place in relatively low oxygen environment by the dilution of inert flue gas. This method has been applied to control NO_X in utility and industrial boiler burners. When applied to automotive engines, this method is frequently called exhaust gas recirculation (EGR).

FGR generally requires large amount of flue gases for the effective control of NO_X, thus requires a larger induced draft fan. In such a case, flame instability may occur due to the increase in oxidizer velocity.

To resolve this problem, fuel induced recirculation (FIR) method was introduced to reduce NO_X emission with less amount of flue gas than FGR (Feese and Turns, 1998 ; Lang, 1994). This method recirculates flue gas in the fuel-side instead of air-side.

Comparable NO_X reduction effect can be achieved with relatively small amount of flue

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gas in FIR than FGR. Based on a simple heat capacity analysis, the reduction in flame temperature resulting from recirculated flue gas should not depend on whether the flue gas is diluted in the air or fuel sides. Considering this, the effectiveness in FIR is noteworthy.

The object of the present study is to investigate the effectiveness of flue gas dilution in turbulent swirl flow. A laboratory scale burner was designed and the flue gas is simulated with N_2 or CO_2 by supplying them either in air-side or fuel-side, to identify the effects of FGR and FIR on NO_X reduction.

2. Experiment

The apparatus consisted of a swirl burner, flow control system, and flame temperature and NO_X measurement setups, as schematically shown in Fig. 1. The burner had a fuel nozzle with twelve holes installed in the center of burner with 90° injection angle. Oxidizer is supplied through a swirler, which provides recirculation zone for flame holding. A 250×250×600 mm square duct was used as a furnace which is made of 25 mm thick insulation board. The fuel was liquefied petroleum gas (LPG) and the oxidizer was compressed air. To simulate exhaust gas recirculation, N_2 and CO_2 gases were used which were supplied in air-side for the FGR case and fuel-side for the FIR case. The flow rates were monitored by mass flow controllers. All the gases were supplied at room temperature.

The flame temperature was measured by R-type thermocouples along the center line of the burner and the composition of exhaust gases, such as NO, CO, CO_2, and O_2, were monitored by a gas analyzer (TESTO 325) at the furnace outlet.

In all experiments, the fuel flow rate was maintained constant at 5 lpm. Two conditions were tested for the FGR cases; (1) the air flow rate was fixed (FA) at 110 lpm, which corresponds to 20% excess air ratio, and the diluents of N_2 or CO_2 were added in the oxidizer stream and (2) the total oxidizer flow rates of the air and diluent were fixed at 150 lpm, to maintain the oxidizer velocity constant (FV). These two test conditions could provide the information on the effects of the variations in oxygen concentration and oxidizer velocity. In the FIR experiments,

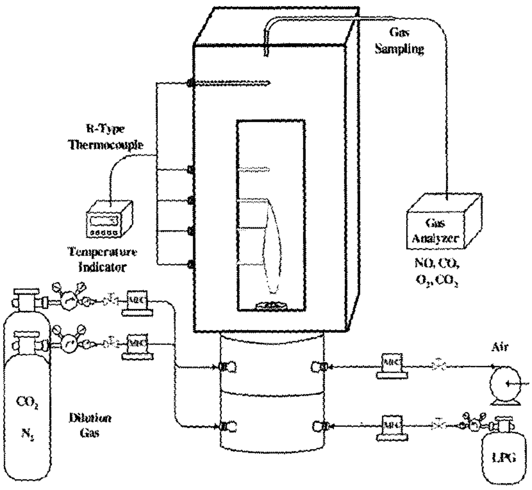

Fig. 1 Schematic of experimental apparatus

Table 1 Experimental conditions

Cases		Fuel (lpm)		Oxidizer (lpm)		Recirculation Ratio (%)
		LPG	Dilutant	Air	Dilutant	
FGR	FA	5	-	110	0～40 V_o=2.83～3.86 m/s	0～34
	FV	5	-	150～110	0～40 V_o=3.86 m/s	0～34
FIR	FD	5	0～15 V_F=8.8～35.2 m/s	110	-	0～13
	FV	5	1.05, 3.45, 6.25, 15 V_F=8.8 m/s	110	-	0～13

the air flow rate was maintained constant at 110 lpm. Also, two conditions were tested ; (1) the diluent was added to LPG for the fixed nozzle diameter (FD) of d=1.0 mm and (2) the nozzle diameter was varied to maintain the fuel velocity constant (FV). For all the FIR experiments, there were 12 holes with the injection angle of 90°. In the FV-FIR case, the nozzle diameter varied 1.0, 1.1, 1.3, 1.5, and 2.0 mm with the degree of diluent addition, while the jet velocity was maintained constant at V_F=8.8 m/s. The experimental conditions are summarized in Table 1.

3. Results and Discussion

3.1 Flue gas recirculation (FGR)

The test was first performed to recirculate flue gas to the oxidizer side. The recirculated dilution gases were simulated by using N_2 or CO_2. Figure 2 shows the flame photographs with the variation of the mole fraction of oxygen X_O in the FA-FGR condition. In the case of X_O=0.21, without having dilution, the flame shows blue luminosity near the fuel nozzle and yellow luminosity in the downstream. This yellow flame disappeared and the flame intensity becomes weaker with the increase in the dilution gas. It has been demonstrated that the flame intensity becomes much weaker with CO_2 dilution than N_2 dilution at the same dilution ratio. This shows the effectiveness of CO_2 dilution which can be implied reducing flame temperature and NO emission.

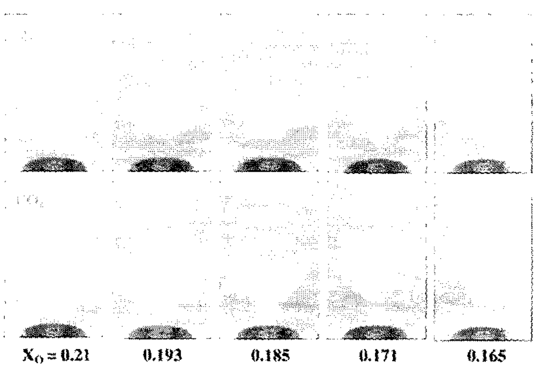

Fig. 2 Flame photos with oxygen mole fraction in FA-FGR cases

Figure 3 shows the temperature distribution along the center line of the burner with N_2 and CO_2 dilutions. The flame temperature gradually decreased from nozzle tip to the downstream and decreased with the decrease in X_O. The peak temperature position for a specified X_O shifted downstream because of the flame lift with dilution. Compared to the N_2 dilution, significant decrease in the temperature occurs with the excessive CO_2 dilution of X_O=0.17 and 0.16. As can be seen in Fig. 2, the flames were much weaker for the two small X_O cases.

In the case of the FA-FGR, the flow velocity of oxidizer increase with the addition of dilution gases. In order to exclude this effect, the FV-FGR was tested having constant oxidizer flowrate, where X_O was varied with dilution. Although not shown, the differences in the temperature profiles between FA-FGR and FV-FIR were minimal since the variation in the oxidizer velocity is small (2.8~3.9 m/s).

Figure 4 shows the NO emission ratio with X_O for both the FA- and FV-FGR cases. The emission ratio is scaled to the base condition of X_O=0.21, where the NO emission was 130 ppm for the 4% O_2 condition. The difference between the FA-FGR and FV-FGR was minimal by the reason stated above. The NO reduction ratio with CO_2 dilution is more effective than the N_2 dilution, because CO_2 has large specific heat to reduce flame temperature. In the case of CO_2

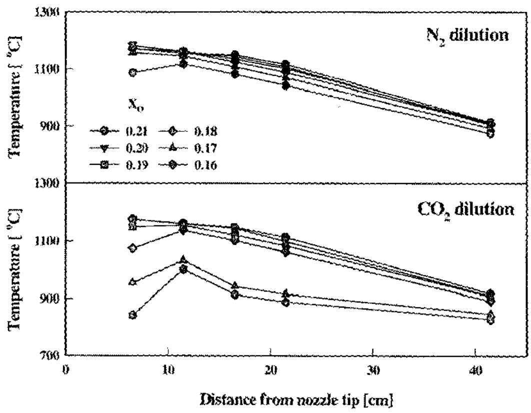

Fig. 3 Flame temperature profile along the center line of burner in FA-FGR cases

dilution, X_O=0.16 shows about 80% NO reduction compared to the base condition. Figure 5 shows the carbon monoxide (CO) emission ratio with the oxygen mole fraction, which decreases with X_O. In general, there is a tradeoff of CO and NO emissions such that CO increases with the decrease in NO. In the present study, however, the CO emission decreases with X_O, showing the similar trend as the NO emission. This can be attributed that the incomplete reaction was reduced by the increase of mixing enhancement in the FA-FGR case and it was shown in Fig. 2 of flame shape, the yellow flame indicating not well mixed fuel and air was disappeared, which caused by the increase of dilution gases. FV-FGR case also showed the same trend of flame shape. All cases are excess O_2 conditions even though low X_0 case.

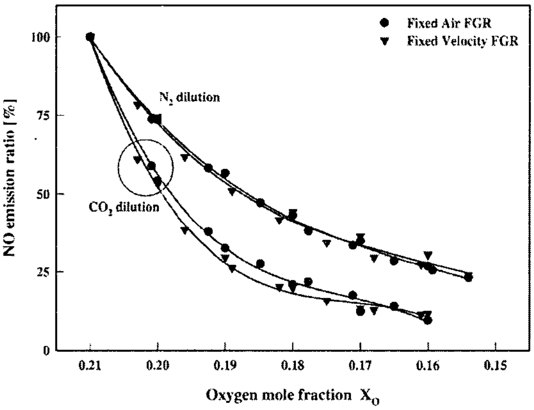

Fig. 4 NO emission ratio with oxygen mole fraction in FGR cases

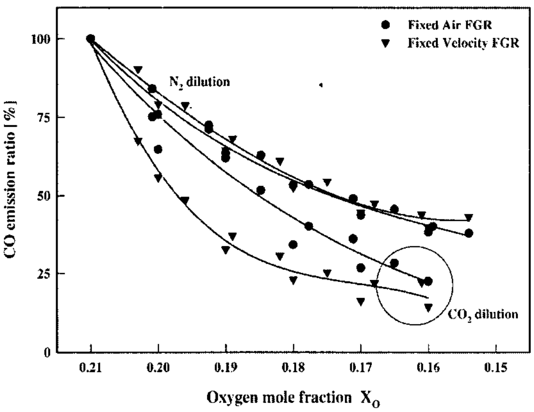

Fig. 5 CO emission ratio with oxygen mole fraction in FGR cases

3.2 Fuel induced recirculation (FIR)

The experiments were preformed for the FIR cases with the dilution gas added to the fuel stream. Figure 6 shows the flame photos of the FIR cases with N_2 dilution. The fuel jet velocity increases with dilution for the FD-FIR while the fuel jet velocity is constant for the FV-FIR by varying the fuel nozzle diameter. The CO_2 dilution cases have the similar trend although the flame intensity is somewhat weaker. For the FA-FIR case, the flame is lifted by the dilution as the fuel jet velocity increases. The yellow luminosity decreases with dilution and the flame is almost invisible for X_F=0.25. For the FV-FIR case, the flame shape was not varied much with the dilution except that the flame intensity becomes weaker.

Figure 7 shows the flame temperature distribution with the distance from the nozzle tip at several X_F with N_2 dilution. The flame temperature distribution with fixed diameter FIR case was varied significantly with X_F, while it was insensitive to X_F for the fixed velocity FIR case. These results are consistent with the flame shapes as was shown in Fig. 6, where the flame shapes do not change much for the FV-FIR case.

Figure 8 shows the NO emission ratio as a function of fuel dilution in the FIR cases. Both

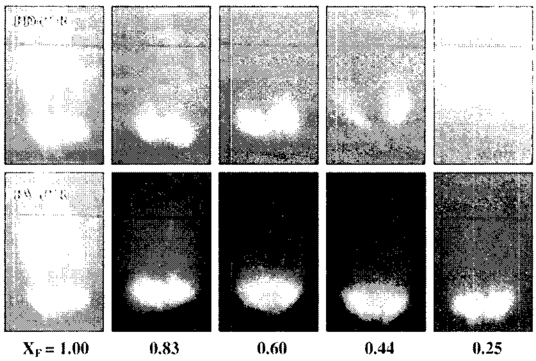

Fig. 6 Flame photos with fuel mole fraction in FIR cases with N_2 dilution

cases have the same trend of decreasing NO production with fuel dilution and the CO_2 case is more effective to reduce NO emission than the N_2 case. Also, the fixed diameter case is more effective than the fixed velocity case. This is due to the increase in the fuel jet velocity with the dilution. As the fuel jet velocity (momentum) increases, fuel and oxidizer mixing enhances with dilution such that the combustion takes place widely in the relatively low oxygen concentration condition. It can be decreased the flame temperature and NO production.

3.3 Comparison of FGR and FIR

It is of interest to test the effectiveness of NO reduction between the FGR and FIR. In this regard, the reduction ratio of NO was compared. For this, the recirculation ratio is introduced as follows.

$$\text{Recirculation ratio (\%)} = \frac{\text{Dilution gas flowrate } (N_2, CO_2) \text{ [lpm]}}{\text{Fuel} + \text{Air flowrate [lpm]}} \quad (1)$$

Figure 9 shows the NO emission ratio with the recirculation ratio in the fixed air FGR and fixed diameter FIR cases. The result shows that FIR is more effective in NO reduction than FGR at the same recirculation ratio. In the case of the N_2 dilution, the recirculation ratio of 30% in the FGR case has the same NO reduction ratio as the recirculation ratio of 8% in the FIR case. This indicates that FIR is more effective in NO reduction with a small quantity of dilution because the increasing ratio of fuel jet velocity is higher than oxidizer jet velocity in the same recirculation ratio. It means that FIR has stronger turbulent intensity than FGR and it enhances fuel and air mixing process in dilution combustion which reduces flame temperature and NO emission.

Figure 10 shows the NO emission ratio with recirculation ratio for the fixed velocity case of the FGR and FIR. It shows that the NO reduction ratio with recirculation ratio is almost same in both the FGR and FIR cases. As shown in

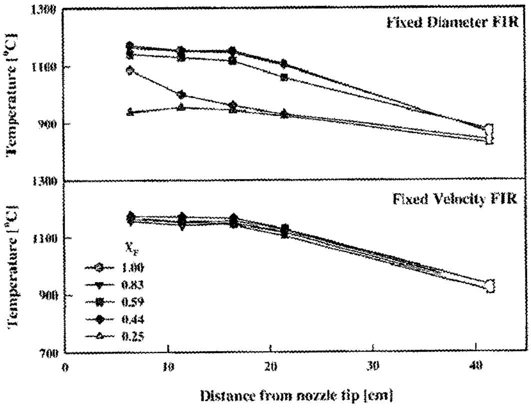

Fig. 7 Flame temperature profile along the centerline of burner in FIR cases with N_2 dilution

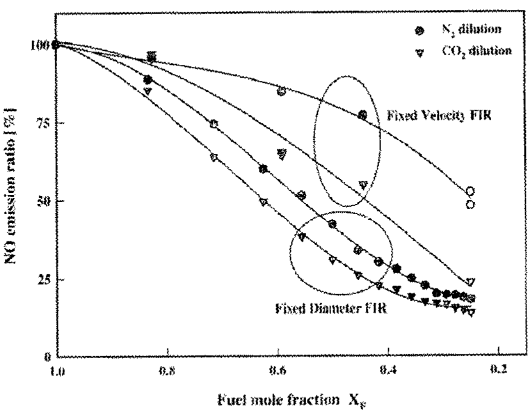

Fig. 8 NO emission ratio with fuel mole fraction in FIR cases

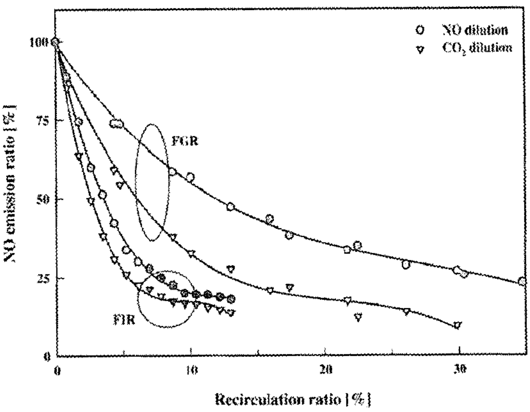

Fig. 9 NO emission ratio with recirculation ratio fo fixed air FGR and fixed diameter FIR case

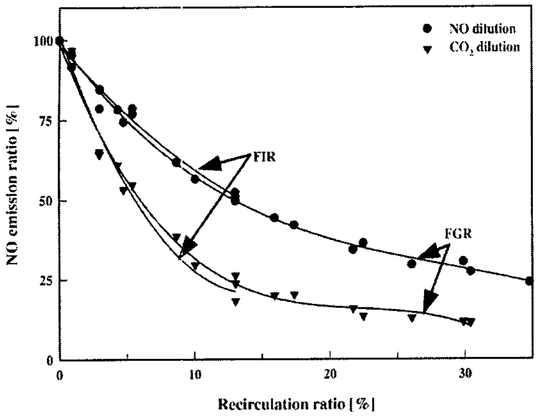

Fig. 10 NO emission ratio with recirculation ratio for fixed velocity FGR and FIR cases

Fig. 9 fixed diameter FIR condition, the higher fuel jet velocity to increase turbulent intensity and mixing is an effective way to reduce NO emission in dilution combustion. But, the fixed velocity FIR case was not affect mixing process so it didn't change flame temperature and NO emission. This result indicates that if the fuel jet velocity is constant, the effect of dilution either to air or fuel side is comparable.

4. Conclusions Remarks

The following conclusion can be drawn in the FGR and FIR experiments.

(1) NO production is reduced by the decrease in oxidizer concentration in the FGR conditions. CO_2 dilution is more effective in the reduction of NO than N_2 because of its higher specific heat.

(2) In the cases of fixed air and fixed velocity FGR cases, the results are comparable in this study because the exit velocity level of oxidizer is too small to affect the flow field and flame temperature.

(3) NO emission ratio is decreased with the dilution ratio in the FIR conditions. The fixed diameter case is more effective in NO reduction than the fixed velocity case, because the combustion takes place in the relatively low oxygen concentration condition resulting from the increase in the dilution ratio caused by the increase of fuel jet velocity in the fixed diameter case.

(4) Comparing the FGR and FIR conditions, in the case of N_2 dilution, the FIR case is more effective in NO reduction with small amounts of dilution than the FGR case. The FGR and FIR has nearly the same effect in NO reduction ratio in the fixed velocity conditions, implying that the flow velocity has significant role in NO reduction.

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