Numerical Investigation of Influence of Dilution in Air and Fuel Sides on MILD Combustion Burner

H.Oryani, Sh.Khalilarya , S.Jafarmadar, H.Khatamnezhad and S.Majidyfar

department address

Abstract: Understanding of how and where NOx formation occurs is very important for efficient and clean operation of utility burners. FGR is a new method adopted to control NOx formation in combustion chamber. In this method flue gas decreases flame temperature and reaction rate, resulting in the diminish in thermal NOx emission. Recently, it has been accomplished that the entered flue gas in fuel stream, that named, FIR method, could increase a much improved reduction in NOx production per unit mass of recirculated gas, as compared to the conventional FGR in air. In the present study, the MILD combustion regime have been simulated, and result validated with experimental data. In order to modification, variations including, temperature and flow of air inlet are performed. Also the effect of FGR/FIR methods on NOx reduction by using CO_2, H_2O, and N_2 as diluents gases are investigated. Results show that FIR is more effective to reduce NOx emission than FGR in the same recirculation ratio of dilution gas, and H_2O dilutor because of large specific heat, is more effective compared to CO_2 and N_2 gases, Also with increasing of velocity and flow of air inlet, the thermal NO_X concentration decreases.

Key words: MILD combustion, CFD, Flue gas recirculation (FGR), Fuel induced recirculation (FIR), NOx emission.

INTRODUCTION

Moderate and intense low oxygen dilution (MILD) combustion that known as flameless oxidation is a newly developed and technique for achieving low emission of pollutants and improve thermal efficiency of combustion systems (Cavaliere, 2004; Tsuji, 2003).

The MILD combustion is characterized by both an elevated temperature of reactants and low temperature increase in the combustion process. It is also called flameless because under optimized conditions the oxidation appears with no visible or audible flame. The main operation principle for this combustion regime is in the concept of exhaust gas recirculation and air preheat. The heat from the exhaust gases is used to increase the temperature of the oxidant stream and the exhaust gases are used to dilute the oxidant stream to reduce the oxygen mass fraction and maintain low temperature in the combustion zone (Murer, 2006).

From a technological point of view, the first requirement for MILD combustion, reactant temperature above the self-ignition temperature, may be achieved by preheating the fuel, the oxidizer, or both. The second requirement, large entrainment of inert species in the reaction region, may be achieved in different ways by either internal or external recirculation of exhaust gases (Galletti, 2007). Katsuki and Hasegawa (1998) investigated effects of heat-recirculating combustion under highly preheated air conditions (1200–1600 K) in industrial furnaces with MILD combustion regime. Murer and Pesenti (2006) simulated flameless combustion of natural gas in a laboratory scale furnace. They investigation numerically and experimentally two regimes of combustion according to the chamber temperature. Choi and Katsuki (2001) investigated controlled of NOx formation by the mixing the fuel and the preheated air in flameless oxidation of industrial glass furnaces. Flamme (2004) investigated the applicability of modification MILD combustion burners to gas turbines with lean premixed combustion. Coelho and Peters (2001) shows applicability flamelet approach in furnace with MILD combustion mode and investigated turbulence/chemistry interactions.

B.B. Dally (2002) pointed out effect of fuel mixture on moderate and intense low oxygen dilution combustion, they investigated numerically influence of two inert gas CO_2 and N_2 on NO_X formation. Sabia *et al.* (2006) studied MILD combustion conditions for hydrogen-oxygen on different amounts of steam. They analyzed combustion mechanisms and ignition delay time. In year of 2004, Cho and Chung (2004) investigated the feasibility of flue gas dilution in air and fuel sides in a laboratory furnace.

Corresponding Author: H.Oryani,

They reported the NO_X emission as experimentally. lean homogeneous combustion, low oxygen combustion and other inert gas dilution are practical methods to reduce flame temperature. Essentially, one of the well-known methods to control NOx emission is flue gas recirculation (FGR). A partial of exhaust gases is entered in oxidizer (air) side in FGR, which reduces flame temperature and NOx production, since combustion occurs in relatively low oxygen condition by the dilution with inert flue gas. This idea has been applied to control NOx formation in industrial boiler and utility gas turbine burners. Sometimes, because of the increase of oxidizer velocity, flame instability may be occur. To resolve this problem, fuel induced recirculation (FIR) method was accomplished to reduce NOx emission with low content of exhaust gas than FGR. This method recirculates exhaust gas in the fuel-side instead of air-side. So that FIR method could be effectiveness procedure rather than FGR. The object of the present study is to reports on the effects of air temperature and air flow rate on the structure of MILD combustion operating in a recuperating furnace as a mean of controlling the flame and NO_X emission, and then investigate the effectiveness of flue gas dilution in turbulent flow. After modeling of MILD combustion burner, the flue gas has been simulated with N_2 or CO_2 and H_2O by supplying them either in air-side or fuel-side, to identify the effects of FGR and FIR on NOx reduction.

Calculation Procedure:

At the present work, the commercial code Fluent 12 by Ansys Inc, has been used for modeling of an industrial burner that operating in MILD combustion. Table 1 and 2, show details of typical data and physical model of this burner, respectively.

MILD Combustion Burner Geometrical Description:

The geometrical sizes of the MILD combustion burner indicated on Figure 1. The combustion chamber is surrounded by a radiant tube that upper end part of it is closed. The burner is suited for all applications where the combust on environment has to be kept separated from the media to be heated (e.g., furnaces for steel formation, glass making). This burner operates with an internal recirculation of exhaust gases which is promoted by a long flame tube positioned inside the burner. The axisymmetric model is shown in Figure 2, the structured grid consisted of 130,000 hexahedra, divided in four layers with an angular sector of 5°. MILD combustion burners are usually 2D simulations (Al-Halbouni, 2004).
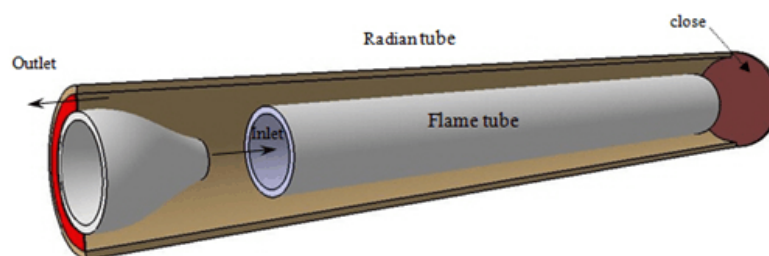

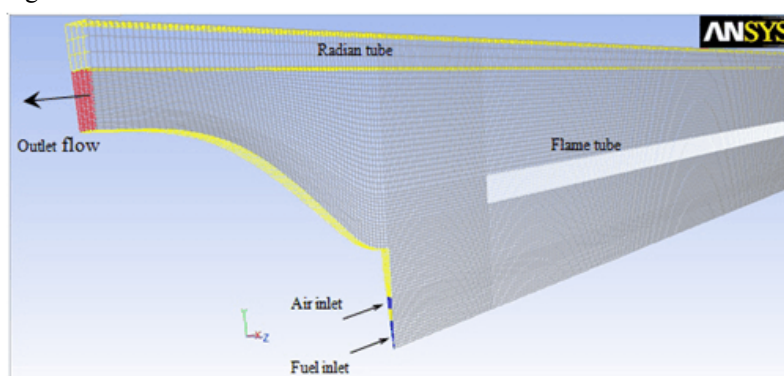**Fig. 1:** Configuration geometrical of the MILD combustion burner.

Fig. 2: Axisymmetric grids of burner.

Table 1: Typical data of the MILD combustion burner.

Model	Axisymmetric
power	13 KW
fuel	CH4
Fuel flow rate	0.000267 kg/s
Air flow rate	0.0067 kg/s
Radiant tube diameter	0.045 m
Flame tube diameter	0.02 m
Burner Length	0.58 m
Flame tube Length	0.41 m
Fuel temperature	298 K

Table 2: Burner Physical model and reactive scheme.

Chemistry	Combustion Model: EDM/FRC, One- steps global mechanism: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
Turbulence model	k- ε (Standard).The first constant of the dissipation transport equation $C_{\varepsilon 1}$ was set equal to 1.6 instead of 1.44 as suggested by Morse in order to overcome the deficiency of the standard model k- ε in predicting round jets properly (Morse, 1977).
Radiation Model	DOM (Discrete Ordinate Model) Absorption coefficient: WSGGM

Table 3: Total NOx for burner in (A_{air} = 88 mm^2).

Experimental data	48 ppm
Numerical model	57.4 ppm

NO_x Formation Model:

NOx formation during the combustion process occurs mainly through the oxidation of nitrogen in the combustion air by two mechanisms known as thermal NOx and prompt NOx. The rate of thermal NOx formation is directly affected by the combustion zone temperature and the oxygen concentration. Thermal NOx can be reduced by decreasing the flame temperature or limiting the oxygen concentration. The formation of NOx in burners is a very complicated problem due to turbulent, chemical kinetic and many parameters that influence its formation process. Prompt NOx is produced by high-speed reactions at the flame front, and is most prevalent in rich flames. The formation of thermal NOx is determined by a set of highly temperature-dependent chemical reactions known as the extended Zeldovich mechanism. The principal reactions governing the formation of thermal NOx from molecular nitrogen are as follows:

$$O + N2 \leftrightarrow N + NO \tag{7}$$

$$N + O2 \leftrightarrow O + NO \tag{8}$$

A third reaction has been shown to contribute to the formation of thermal NOx, particularly at near-stoichiometric conditions and in fuel-rich mixtures:

$$N + OH \leftrightarrow H + NO \tag{9}$$

The rate of formation of NOx is significant only at high temperatures (greater than 1800 K) because oxidation of nitrogen requires the breaking of the strong N_2 triple bond (dissociation energy of 941 kJ/gmol)

RESULTS AND DISCUSSION

Burner Validation:

 Radial temperature distributions under two different axial coordinate in one Specific case ($A_{air_{in}}$= 88   mm^2) has been compared with experimental data of Chiara Galletti, and has been indicated in Figure 3 (Galletti et al., 2007), as can be seen, the temperature distribution of burner at present model that has good agreement with experimental data.

Effect of Increasing Air Flow Inlet:

As mentioned in the Introduction, in this section investigate the effect of air excess fraction on temperature profiles and NO_X product.

Figure. 4 shows, the temperature profiles and total NOx in the case of air excess variations. It was found that, when the air excess increases from 46% to 74%, maximum temperature observed in the burner is decreases from 2090 K to 2044 K, average temperature of combustion chamber decreases from 1844 K to 1820 K, and also because of increase exhaust gas recirculation and reaction dilution, NO_X product decreases from 54.6 to 29.4 ppm. This may be easily imputed to the increase thermal capacity associated with the recalculating nitrogen causes to decreasing the temperate and thermal NO product. Also because of sympathy flame due to dilution inert gas in reaction region value of prompt NOx reduces.

Therefore, with an air excess of 16% the maximum temperature observed in the burner increases to 2265 K and average temperature rise to 1992 K, In addition, NOx emission was also found to increase about 272 ppm. When oxygen concentration in the reaction zone diminishes with decreases air excess, NOx formation become damping, the enhanced temperatures govern the NOx formation and lead to a strong increase of NOx emissions.

Effect of Increasing Air Temperature:
The temperature of air preheat affects on flame temperature, this effect cause to variation in mild combustion regime and NO_X formation.

Figure 5, shows the influence of combustion air temperature on temperature profile of burner and NO_X emission. Also indicated low NOx emission (42 ppm) at the start of MILD combustion mode, that increases gradually with the increase of the air inlet. It shows approximately a linear correlation between the air temperature and the burner maximum temperatures in the range above 1000 ∘C. This Figure points to an upper limit of the MILD combustion mode where a maximum temperature is also required to define the MILD combustion regime. Figure 5, indicates that when air temperature increases from 1000 K to 1250 K, furnace average temperature increases up to T = 110 K, maximum temperature goes up from 2329 K and value of NO_X increases from 42 to 867 ppm. It is known that value of NO_X emission enhance with air temperature. It appears that thermal NO formation is highly dependent on temperature. In fact, the thermal NOx production rate approximately doubles for every 50 K temperature increase beyond 1100 K.

Effect of Fuel and Air Dilution with CO_2, N_2, H_2O:
To investigating of exhaust gas recirculation, N2 ,CO_2, and H_2O gases were used. In all process, the fuel flow rate has been maintained constant at 0.00267 kg/s. For FGR cases; the air flow rate has been fixed at 0.0067 kg/s, which corresponds to 46% excess air ratio, and the diluents of N_2, CO_2 and H_2O adds in the oxidizer stream. In the FIR cases, the air flow rate has been maintained constant at 0.0067 kg/s and the diluents adds to fuel.

Flue Gas Recirculation (FGR):
The study was first performed to recalculate flue gas to the oxidizer side. The recirculated dilution gases has been investigated by using N_2 ,CO_2 or H_2O.

Figure 6 and 7 indicated temperature profiles and value of NO_X product in the case of X_O (X_O is oxygen mass fraction). X_O = 0.23 has been considered without dilution. Figure 6, shows that the average and maximum temperature of burner has been reduced with the decrease in Xo. For example by dilution with CO_2, the average temperature reduces from 1842 to 1809 K, maximum temperature decreases from 2099 to 1920 K, so flame temperature gradually reduces in the downstream and maximum temperature position with reduces of Xo, shifted to downstream. and NO_X emission decreases from 57.4 to 6.73 ppm that shows in Figure 7.

Dilution have cooling effect on the flame locally, and this decreases of local temperature reason of reduces the NO_X emission.

By adding inert gases, exhaust gas recirculation increases the turbulence intensity enhances and this act leads to mixing intensification, in other word incomplete reaction was reduced by dilution. So Can be said carbon monoxide (CO) emission ratio reduces with dilution and decreases of the oxygen mass fraction. Also dilution with CO_2 cause to suppress the soot formation, because of the lean conditions in the combustion chamber, due to the large dilution levels (Cavaliere and Joannon, 2004; Tsuji et al., 2003).

Comparison of dilutors indicated more decrease in the temperature occurs with H_2O dilution in Xo = 0.188 and 0.186. as can be seen in Figure 7, Dilution with H_2O more decreases the value of the NO_X rather than N_2 and CO_2 gases, and likewise CO_2 diluter is more effective to reduce NO_X emission than the N_2 diluter. because of the specific heats of H_2O more than N_2 and CO_2, and specific heats of CO_2 more than N_2. And this effect intensive for temperature up to 1500 K due to the ratio of the specific heats of H_2O to that of N_2, CO_2 changes with respect to temperature. For example the ratio of specific heats of CO_2 to that of N_2 in temperature of 1500 K equal 1.066 and in 300 K is 0.817.

Fuel Induced Recirculation (FIR):

As mentioned, in FIR cases the dilution gas added to the fuel stream. In this state for enhance the mixing of fuel with air preheated and rise up turbulent flow, fuel inlet cross sectional area reduces to one third. Figure 8 and 9 show, temperature profiles and NO_X product in the case of X_F (X_F is Fuel mass fraction). $X_F = 1$ has been consider without dilution. Fuel dilution with inert gases causes to reduction in NO_X emission and suppresses any flame propagation inside the furnace. For example Figure 8 shows, that by dilution with CO_2 the average temperature reduces from 1842 to 1753 K, maximum temperature decreases from 2099 to 1912 K, and Figure 9, shows NO_X emission decreases from 57.4 to 7.14 ppm.

When the fuel jet velocity increases with dilution, the maximum temperature of burner, or peak temperature of flame is reduces. In other word, 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_X production.

Such dilution results in a shift in the lean side toward the stoichiometric mixture fraction, which has the highest scalar of dissipation and ensures the mixture of fuel and air is diluted before it can react.

Comparison of diluters shows, more reduces in the temperature occurs with H_2O dilution. As can be shown in Figure 9, Dilution with H_2O is more effective to reduce NO_X emission rather than other diluters.

Comparison of FGR and FIR:

It is of benefit to investigate the effectiveness of NO_X reduction between the FGR and FIR. In order to approach this purpose, the recirculation ratio is reported as follows.

$$\text{Recirculation ratio (\%)} = \frac{\text{Dilution gas flowrate (N2, CO2) [lpm]}}{\text{Fuel} + \text{Air flowrate [lpm]}}$$

Figure 10 shows, the NO_X emission ratio with the recirculation ratio in the FGR and FIR cases. The result shows, at the same recirculation ratio, FIR is more effective in NO_X reduction than FGR. For example CO_2 dilutor, has the same NO_X emission at recirculation ratio of 24% in the FGR case toward FIR case at the recirculation ratio of 1.5%. In the other hand FIR is more effective in NOx reduction with a small quantity of dilution due to the fuel jet velocity is higher than oxidizer jet velocity in the same recirculation ratio, in addition to high jet velocity lead to stronger turbulent intensity in reaction zone and enhances fuel and air mixing process in dilution combustion, which this phenomena reduces flame temperature and NOx emission.
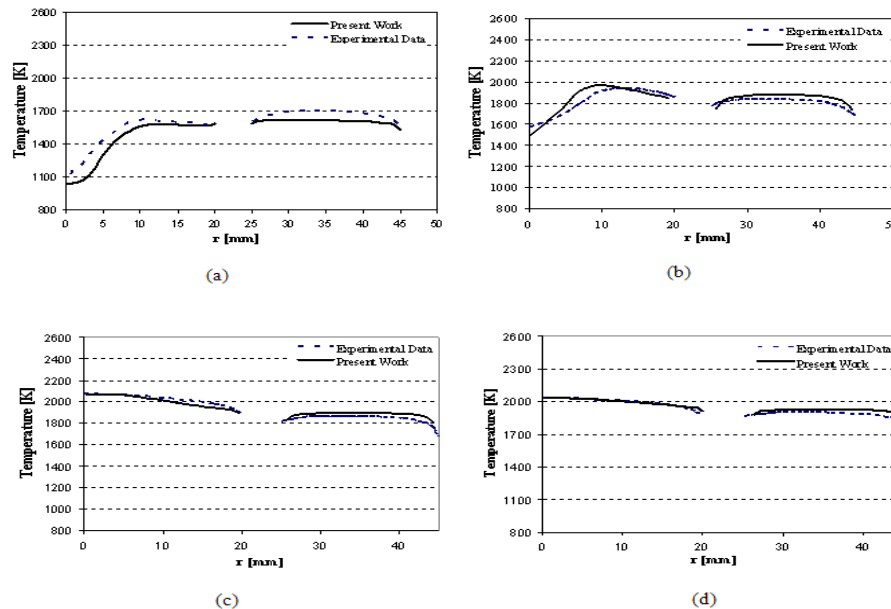

Fig. 3: Radial profiles of temperature for ($A_{air} = 88$ mm^2) under different axial.
Coordinate: (a) x = 150; (b) x = 250; (c) x = 350; (d) x = 450mm. Burner load $Q_{in} = 10.42$KW
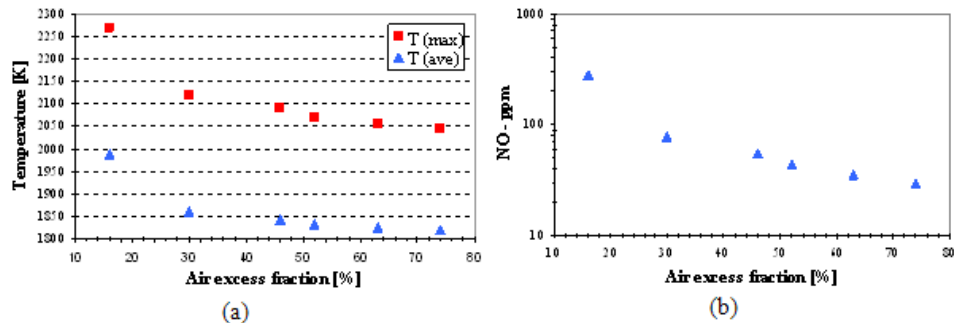
Fig. 4: Influence of air flow inlet on: (a) temperature profiles and (b) NO_X product.
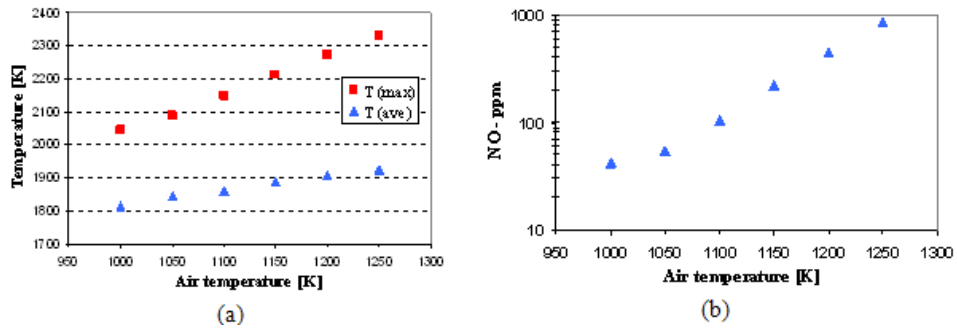

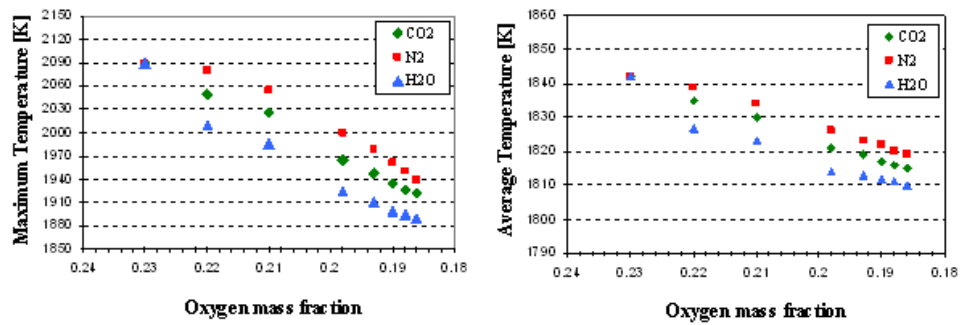**Fig. 5:** Influence of combustion air temperature on: (a) temperature profiles and (b) NO_X product.

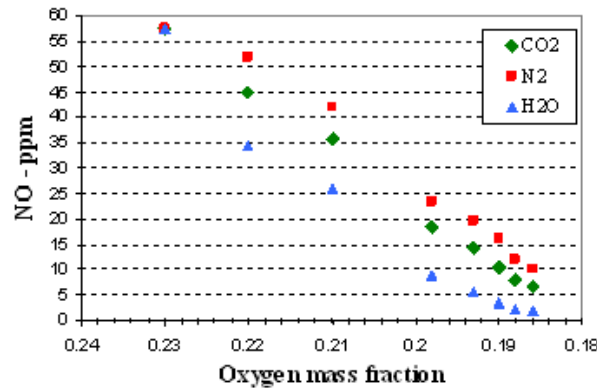**Fig. 6:** Temperature profiles with oxygen mass fraction in FGR cases..

Fig. 7: NO_X emission ratio with oxygen mass fraction in FGR cases.
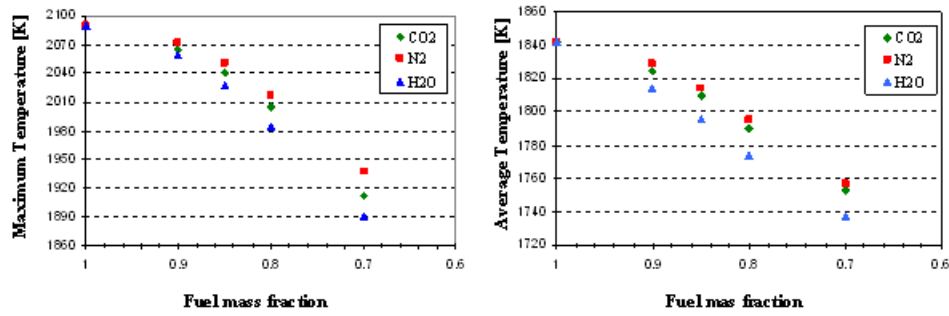
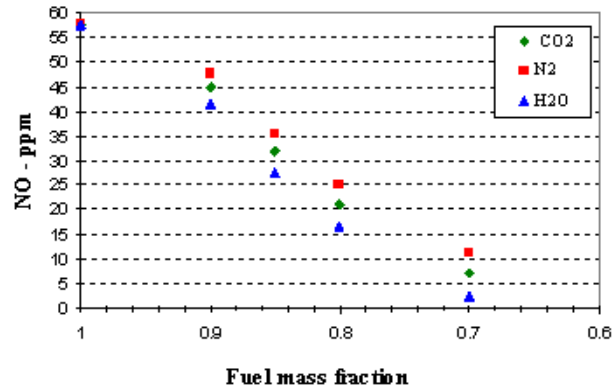**Fig. 8:** Temperature profiles with fuel mass fraction in FIR cases.

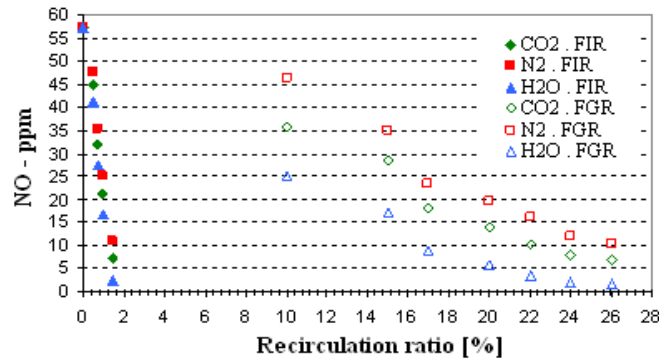**Fig. 9:** NO$_X$ emission ratio with fuel mass fraction in FIR cases.

Fig. 10: NOx emission ratio with recirculation ratio for FGR and FIR cases.

Conclusions:

MILD combustion is define as process include widely states of the temperature range and overall oxygen mass fraction. Major aim of this technique, is approach to very small NOx production, and avoid from high temperatures. Hence, it is obligatory to keep most of the burner at or below a limit that suppress NOx formation. A numerical investigation through computational fluid dynamics on a industrial burner with recuperative MILD combustion has been exhibited. Obtained results from this study are reported as follow:

- If air flow inlet increases, maximum and average temperature observed in the burner reduces, and due to increase of exhaust gas recirculation and reaction dilution, NOx product decreases. Accordingly when the air excess increases from 46% to 74%, maximum temperature observed in the burner is decreases from 2090 K to 2044 K, average temperature of combustion chamber decreases from 1844 K to 1820 K, and so NO$_X$ product decreases from 54.6 to 29.4 ppm.
- While the inlet air temperature increases, the furnace maximum temperature and average temperature increases. For example when air temperature increases from 1000 K to

- 1250 K, furnace average temperature increases up to T = 110 K, maximum temperature goes up from 2046 2329 K, and value of NO_X increases from 42 to 867 ppm. Results shows that value of thermal NOx production rate doubles for every 50 K temperature increase beyond 1100 K.
- NO_X production is reduced by the decrease in oxidizer concentration in the FGR conditions. H_2O diluter because of high specific heat dilutor is more effective in the reduction of NO_X than N_2 and CO_2.
- Fuel dilution in the FIR condition cause to a reduction in NO_X emission and suppresses any flame propagation inside the furnace
- Comparing the FGR and FIR conditions in the case of N_2, CO_2 and H_2O dilution, indicates that the FIR case is more effective in NO_X reduction than the FGR case with small amounts of dilution.

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