Influence of Dilution and Lean-premixed on Mild Combustion in an Industrial Burner

Sh.Khalilarya, H.Oryani, S.Jafarmadar, H.Khatamnezhad**,** A.Nemati

Abstract—Understanding of how and where NOx formation occurs in industrial burner is very important for efficient and clean operation of utility burners. Also the importance of this problem is mainly due to its relation to the pollutants produced by more burners used widely of gas turbine in thermal power plants and glass and steel industry.

In this article, a numerical model of an industrial burner operating in MILD combustion is validated with experimental data.. Then influence of air flow rate and air temperature on combustor temperature profiles and NO_X product are investigated. In order to modification this study reports on the effects of fuel and air dilution (with inert gases H_2O, CO_2, N_2), and also influence of lean-premixed of fuel, on the temperature profiles and NO_X emission.

Conservation equations of mass, momentum and energy, and transport equations of species concentrations, turbulence, combustion and radiation modeling in addition to NO modeling equations were solved together to present temperature and NO distribution inside the burner.

The results shows that dilution, cause to a reduction in value of temperature and NO_X emission, and suppresses any flame propagation inside the furnace and made the flame inside the furnace invisible. Dilution with H_2O rather than N_2 and CO_2 decreases further the value of the NO_X. Also with raise of lean-premix level, local temperature of burner and the value of NO_X product are decreases because of premixing prevents local "hot spots" within the combustor volume that can lead to significant NOx formation. Also lean-premixing of fuel with air cause to amount of air in reaction zone is reach more than amount that supplied as is actually needed to burn the fuel and this act lead to limiting NOx formation

Keywords—Mild combustion, Flameless, Numerical simulation, Burner, CFD.

I. INTRODUCTION

MILD (Moderate or intense low oxygen dilution) combustion and improvement over that known as flameless oxidation is a newly developed and implemented technique for achieving low emission of pollutants and improve thermal efficiency of combustion systems [1–3].

The MILD combustion is characterized by both an elevated temperature of reactants and low temperature increase in the combustion process. These features are the results of several technological demands coming from different application fields.

It is also called flameless because under optimized conditions the oxidation proceeds with no visible or audible flame. The main operation principle for this techniquelies in the concept of exhaust gas and heat recirculation. The heat from the exhaust gases is used to raise the temperature of the oxidant stream and the exhaust gases are used to dilute the oxidant stream to reduce the oxygen concentration and maintain low temperature in the combustion zone [4].

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.

Katsuki and Hasegawa [5] investigated effects of heat-recirculating combustion under highly preheated air conditions (1200–1600 K) in industrial furnaces with MILD combustion. They defined the highly preheated air combustion (HPAC) as that air temperature at which gaseous fuel is ignited automatically in it and continuous combustion is sustained.

Advantage of this combustion technology, is flame stabilization (because of reactants' temperature exceeds the self-ignition temperature) homogenous temperature, decreases the temperature gradients, control of maximum temperatures with beneficial effects on materials.

Several studies have been devoted to understanding its operational conditions [6] as well as its mechanisms and critical parameters [7]. An extensive review on MILD combustion features considering physical, chemical, and thermodynamic aspects has been provided by Cavaliere and de Joannon[8].

Choi and Katsuki [9] investigated controlled of NOx formation by the mixing the fuel and the preheated air in flameless oxidation of industrial glass furnaces. Flamme [10] investigated the applicability of modification MILD combustion burners to gas turbines with lean premixed combustion. Coelho and Peters [11] shows applicability flamelet approach in furnace with MILD combustion mode

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and investigated turbulence/chemistry interactions.

Also, B.B. Dally [12] 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.

In this study, a numerical model of an industrial burner operating in MILD combustion is validated with experimental data. Then influence of air flow rate and air temperature on combustor temperature profiles and NO_X product are investigated. The 2D axisymmetric model has been investigated as this model is commonly adopted [15,16] because of low computational cost. This paper reports on the effects of fuel and air dilution (with inert gases H_2O, CO_2, N_2) on the structure of MILD combustion operating in a recuperating furnace as a mean of controlling the local temperature, flame, and NO_X emission at different heat loads. And in continue, the effects of lean premixed on temperature profiles, and NOx emission are also reported.

II. NUMERICAL ANALYSIS

At present work by using the commercial Ansys Fluent 12 an industrial burner of Chiara Galletti et al [13] that operating in MILD combustion, was modeled. Table I and II shows details of typical data and physical model of burner. This

A. Description of the Model

The geometrical sizes of the MILD combustion burner indicated on Fig.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.

Fig. 1 Configuration of the MILD combustion burner

TABLE I
TYPICAL DATA OF MILD COMBUSTION BURNER

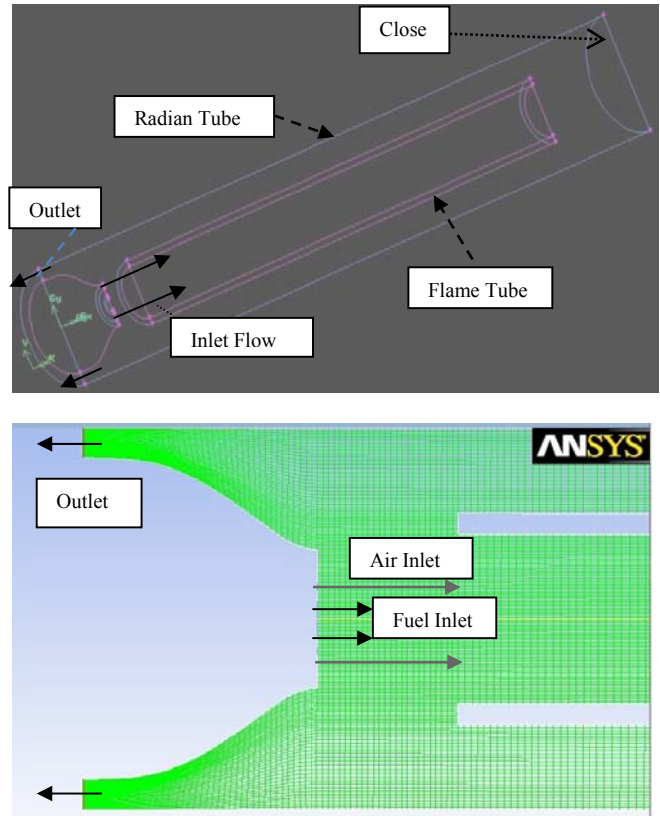| power	13 KW
fuel	CH4
Fuel flow rate	0.000267 kg/s
Air flow rate	0.0067 kg/s
Radiant tube diameter	0.045 m
Flame tube diameter	0.02 m
Burner Length	0.58 m
Flame tube Length	0.41 m
Fuel temperature	298 K
Air inlet cross sectional area	88 mm^2

TABLE II
BURNER PHYSICAL MODEL AND REACTIVE SHEME

Chemistry	Combustion Model: EDM/FRC, One- steps global mechanism: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
Turbulence model	$k - \varepsilon$ (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 [14]in order to overcome the deficiency of the standard k–ε model in predicting round jets properly.
Radiation Model	DOM (Discrete Ordinate Model) Absorption coefficient: WSGGM
Numerical approach	
Mesh type	Hexahedra
Solver	Segregated

The model of the burner is 2D and axisymmetric. The structured grid consisted of 130,000 hexahedra. Simulations available in the literature of recuperative MILD combustion burners are usually 2D simulations [15,16]. Because of the larger predicted recirculation degrees and high computational, 2D models are expected instead 3D model to underestimate Temperature distributions and NO emissions.

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B. Mathematical Formulation

Most fuels are fast burning, and the overall rate of reaction is controlled by turbulent Mixing. When you choose to solve conservation equations for chemical species, in eddy-dissipation/finite rate chemistry model, reaction rates are assumed to be controlled by the turbulence mixing rate, and the Arrhenius rate, then chooses the lower of the two rates to be inserted in the species' transport equation

Turbulence-chemistry interaction model, based on the work of Magnussen and Hjertager [17], called the eddy-dissipation model.

Basic equation that solve in this model inclusive:

1. Continuum Equation

$$\frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x_j}(\rho U_j)$$

2. Energy Equation

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(\vec{\upsilon}(\rho E + p)) = \nabla.(k_{eff}\nabla T - \sum h_j \vec{J}_j + (\overline{\overline{\tau}}_{eff}.\vec{\upsilon})) + S_h$$

Where k_{eff} is the effective conductivity ($k + k_t$, where k_t is the turbulent thermal conductivity, defined according to the turbulence model being used), and j_j is the diffusion flux of species j. S_h includes the heat of chemical reaction, and any other volumetric heat sources you have defined.

3. Transport Equation for the Standard $k - \varepsilon$ Model

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + G_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - G_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon$$

G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy due to buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, $C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}$ are constants. S_k and S_ε are user-defined source terms.

4. Species Transport Equations

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla.(\rho\vec{\upsilon}Y_j) = -\nabla.\vec{J}_i + R_i$$

Where R_i is the net rate of production of species i by chemical reaction. J_i is the diffusion flux of species i.

$$\vec{J}_i = -\rho D_{i,m}\nabla Y_i$$

Here $D_{i.m}$ is the diffusion coefficient for species i in the mixture and Y_j is the mass fraction of species j .

C. NOx Formation

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 simplified one-step kinetic mechanism and set of highly temperature-dependent chemical reactions known as the extended Zeldovich mechanism by assuming a steady state for the N radicals and relating the O radical concentration to that of oxygen by means of the dissociation reaction [18]. The resulting rate is expressed as:

$$\dot{w}_{NO,thermal} = W_{NO}k_{thermal}[O_2]^{1/2}[N_2] \ (kg/m^3 s)$$

$$k_{thermal} = \frac{4.52 \times 10^{15}}{\sqrt{T}}\exp(-\frac{69.466K}{T}) \ \ (\frac{m^3 k}{kmol.s^2})^{1/2}$$

The prompt NO formation was modeled using a similar approach, according to the one step mechanism proposed by De Soete [19],

$$\dot{w}_{NO,prompt} = W_{NO}k_{prompt}[O_2]^{1/2}[N_2][F] \times (\frac{W_{mix}}{\rho})(\frac{kg}{m^3.s})$$
$$(kg/m^3 s)$$
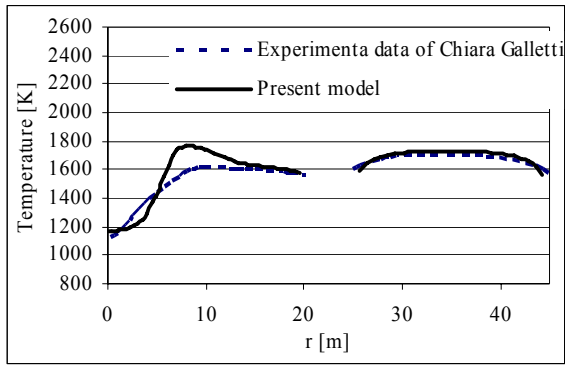
$$k_{prompt} = 1.2 \times 10^6 \exp(-\frac{30215K}{T})(\frac{1}{s})$$

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 N2 triple bond(dissociation energy of 941 kJ/gmol).
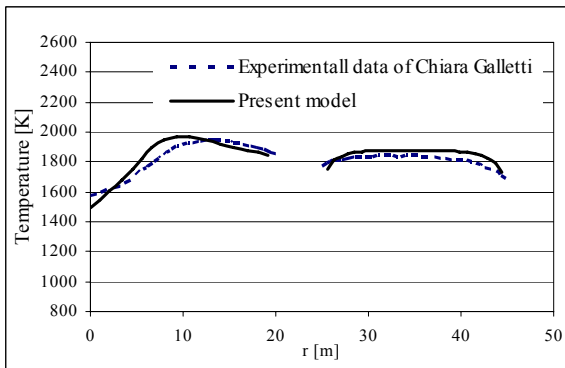
III. RESULTS AND DISCUSSION
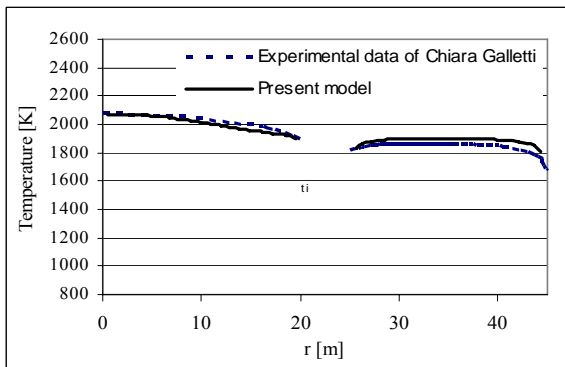
A. Burner Validation

Radial temperature distributions and NOx product in one Specific case ($A_{air_{in}}$ =88 mm^2) indicated in Fig. 2and table III, also validate with experimental data of Chiara Galletti et al. [13],which the temperature in burner that has good agreement with present numerical model.
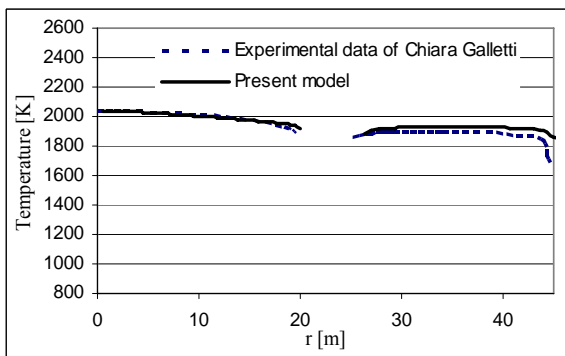
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(a)

(b)

(c)

(d)

Fig. 2 Radial profiles of temperature for ($A_{air_{in}}$ =88 mm^2) under different axial coordinate : (a) x = 150; (b) x = 250; (c) x = 350; (d)x = 450 mm. Burner load $\dot{Q}_{in}$ = 10.42 KW

The total NOx calculated is 57ppm, that good agreement with experimental data of Chiara Galletti.

TABLE III
TOTAL NO$_X$ OF BURNER ($A_{air_{in}}$ =88 mm^2)

| Experimental data	48 ppm
Present model	57.4 ppm

B. Effect of Increasing Air Flow Inlet

Fig. 3 shows the temperature profiles and total NOx with air excess variations. It was found that for the same air inlet cross sectional area ($A_{air_{in}}$ = 88 mm^2),when the air excess increased from 20 to 50%,maximumtemperature observed in the burner decreased from 2126 to 2038, and NOX product decreased from 70.28 to 22.12 ppm, also because of increase exhaust gas recirculation and reaction dilution, average temperature has been decreased. This may be easily imputed to the increase thermal capacity associated with the recirculating nitrogen causes to decreasing the temperate and then thermal NO product.
Also because of sympathy flame and enter inert gas in reaction region value of prompt NOx reduces.
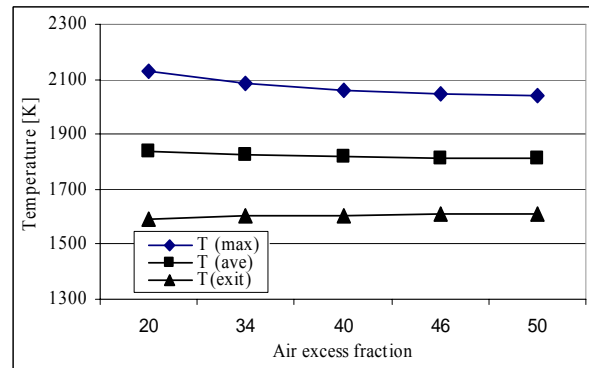
(a)
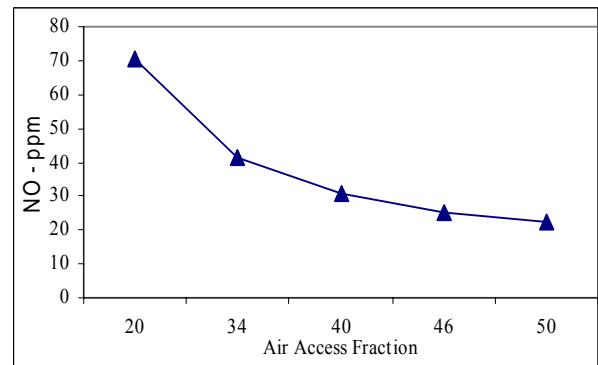
(b)

Fig. 3 Influence of air flow inlet on: (a) temperature profiles and(b) NO$_X$ product. for $A_{air_{in}}$ = 88 mm^2

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C. Effect of Increasing Air temperature

Fig. 4 shows the influence of combustion air temperature on temperature and NO_X emission. As the inlet combustion air temperature increases, the furnace maximum and average temperature increases. Fig. 4 indicates that when air temperature increases from 1050 K to 1250 K furnace average temperature increases up to T = 80 K, and value of NO_X increases from 57 to 867 ppm. It is known that value of NO emission increases with air temperature. It also 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.
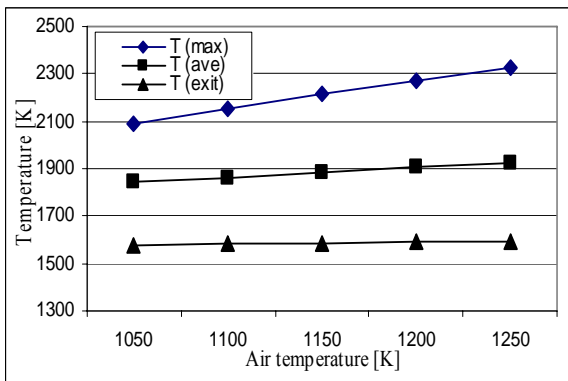

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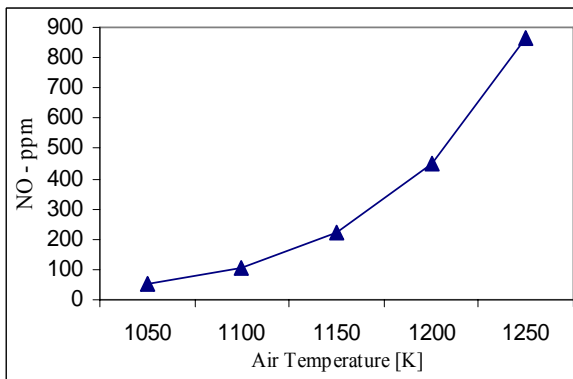
(b)

Fig. 4 Influence of combustion air temperature on: (a) temperature profiles and (b) NO_X product. for $A_{air_{in}} = 88\ mm^2$

D. Effect of fuel and air dilution with CO_2, N_2, H_2O

Fig. 5 shows the value of NOx plotted versus the fuel mass fraction. The fuel stream was diluted using either N_2, CO_2, H_2O to test this approach and its effect on MILD combustion and NOx emission. The NOx is used here as an indicator for the establishment of MILD combustion. The fuel and the air mass flow rates were kept constant during these experiments. Fuel dilution with inert gases causes a reduction in NO_X emission and suppresses any flame propagation inside the furnace. Such dilution results in a shift in the stoichiometric mixture fraction toward the rich side, which has the highest scalar of dissipation and ensures the mixture of fuel and air is

diluted before it can react. Fig 5 indicated that dilution with H_2O rather than N_2 and CO_2 decreases further the value of the NO_X, because of the specific heats of H_2O more further than N2 and CO_2. And this effect accent 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 N_2 in temperature of 1500 K equal 1.066. Fig 5 shows the value of temperature and NO_X more decreases with dilutor of CO_2. Radiation characteristics can also play a role in the flame temperature and that may explain this discrepancy. Also dilution can have cooling effect on the flame locally, and this decreases of local temperature reason of reduces the NO_X emission, but furnace temperature did not change with dilution. Fuel flow access by dilutor lead to increasing of fuel of momentum and numerical value of fuel dissipation and mixing of air and fuel.
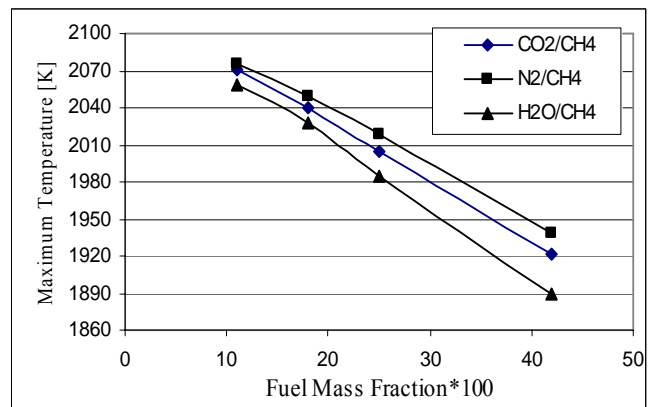

(a)
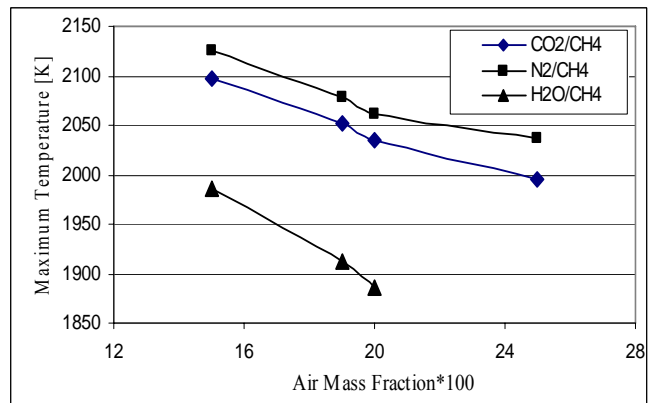
(b)

Fig. 5 Value of maximum temperature and NOX product in effect of fuel dilution. $A_{air_{in}} = 88\ mm^2$

In second state dilutor gases entered from air cross sectional area that value of maximum temperature and NO_X emission has indicated in fig 6. In this state with constant value of flow of air, value of total inlet flow increases and due to increasing of inlet momentum, recirculation of exhaust gases and fix value of oxygen fraction, value of maximum and average temperature and NO_X product decreases.

Also dilution with CO_2 cause to suppress the soot

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formation, because of the lean conditions in the combustion chamber, due to the large dilution levels. In addition, the large CO_2 concentration due to the recirculation of combustion products has a beneficial effect of soot suppression [20].
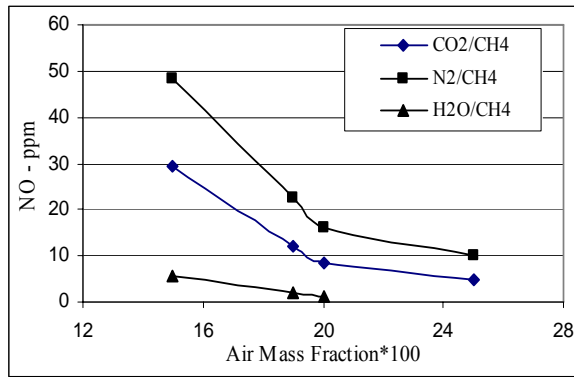
(a)
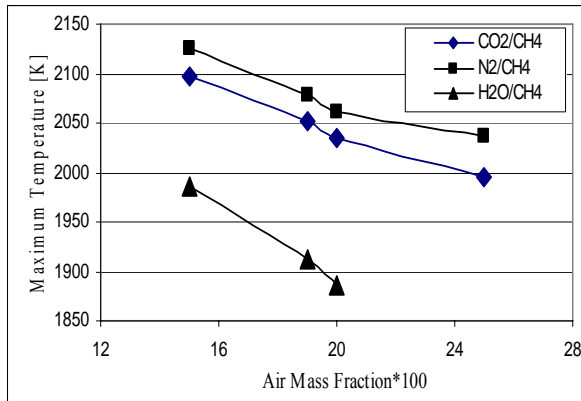
(b)

Fig. 6 Value of maximum temperature and NOX product in effect of air dilution. $A_{air_{in}} = 88 \ mm^2$

E. Effect of Lean-premixed combustion on NO_X and temperature profiles

Lean-premixed combustion means any stationary combustion designed to operate at base load with the air and fuel thoroughly mixed to form a lean mixture before delivery to the combustor. Mixing may occur before or in the combustion chamber. So that indicated in fig 7.A lean premixed may operate in diffusion flame mode during operating conditions such as startup and shutdown, low or transient loads and cold ambient. Premixing prevents local "hot spots" within the combustor volume that can lead to significant NOx formation.

Fig 8 shows temperature and NO_X respect to five lean-premix fractions. In this process value of fuel and air flow are constant. With increasing lean-premix fraction the maximum and average temperature and value of NO_X are decreases.

In lean-premix combustion atmospheric nitrogen (from the combustion air) acts as a diluents, as fuel is mixed with air

upstream of the combustor at deliberately fuel-lean conditions. The f/a ratio typically approaches up of the ideal stoichiometric level, meaning that amount of air is reach more than amount that supplied as is actually needed to burn the fuel. This excess air is a key to limiting NOx formation, as very lean conditions cannot produce the high temperatures that create thermal NOx. Fig 8 shows, if lean-premix fraction increases to 20%, maximum temperature observed in the burner decreased from 2090 K to 1889 K, average temperature decreases from 1838 K to 1718 K and NO_X product decreased from 57.4 to 7.14 ppm,
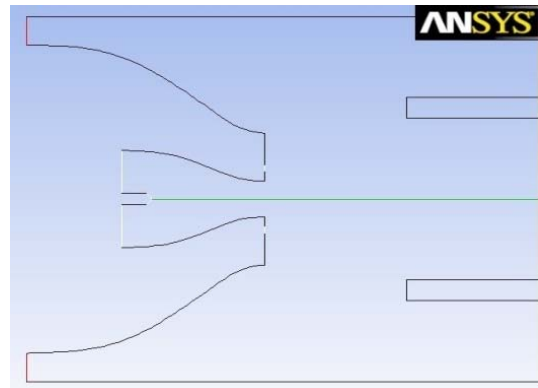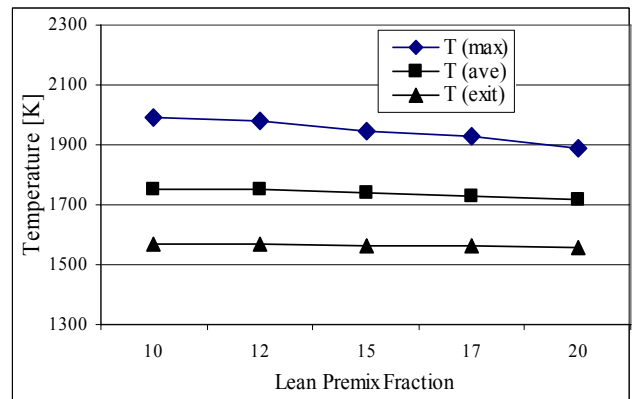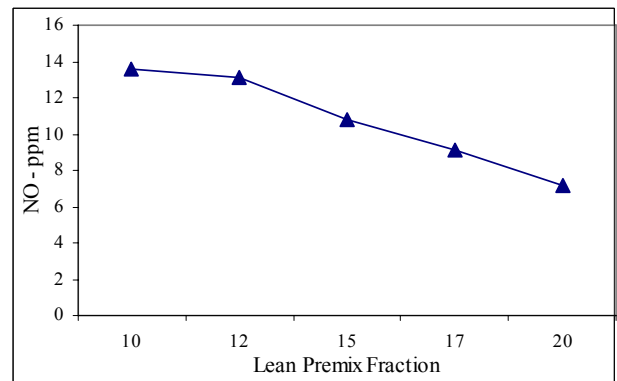

Fig. 7 Configuration of lean-premix combustor

(a)

(b)

Fig. 8 Influence of lean premix fraction on: (a) temperature profiles and (b) NO_X product.

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IV. CONCLUSIONS

A numerical investigation through computational fluid dynamics of a recuperative MILD combustion burner operating in MILD combustion mode has been presented.

MILD combustion will produce very low NOx emissions provided that high temperatures are avoided. Therefore, it is essential to keep most of the furnace at or below a limit that suppress NOx production. Hence an upper limit for the global temperature and oxygen concentration is needed in defining MILD combustion.

- If air flow inlet increases to 50%,maximumtemperature observed in the burner decreased from 2090 K to 2038 K, and NO_x product decreased from 57.4 to 22.12 ppm,
- As the inlet combustion air temperature increases, the furnace maximum temperature and average temperature increases. This phenomena leads to that thermal NOx production rate doubles for every 50 K temperature increase beyond 1100 K.
- Dilution of the fuel stream with inert gases can help achieve MILD combustion and reduced NOx emission due to the shift of the stoichiometric mixture fraction to the rich side where higher scalar dissipation is expected. Hence fuel dilution with inert gases (H_2O, CO_2, N_2) cause to a reduction in NO_X emission and suppresses any flame propagation inside the furnace and made the flame inside the furnace invisible. Dilution with H_2O rather than N_2 and CO_2 decreases further the value of the NO_X, because of the specific heats of H_2O further more than N_2 and CO_2.
- With increasing lean-premix fraction, the maximum and average temperature and value of NO_X are decreases. For example if lean-premix fraction increases to 20%,maximumtemperature observed in the burner decreased from 2090 K to 1889K, average temperature decreases from 1838 K to 1718 K and NO_X product decreased from 57.4 to 7.14 ppm,

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