Influence Of Operating Conditions On NO_x Emission In A Ceramic Furnace Burner

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Abstract—**We intend in this work to model an industrial burner replica of the ceramic tunnel furnace of the Ceramics Modern Society (SOMOCER, TUNISIA). This study aims to investigate numerically the problem of NOx pollution by providing the influence of different operating conditions on temperature and NO distributions. The study is conducted by means of numerical simulations in presence of a reactive flow using the commercial code FLUENT. The 3D Navier-Stokes equations and species transport equations are solved with the eddy-dissipation (*ED*) combustion model. We use *k-ε RNG* turbulence models and the *DTRM* radiation models. The obtained results demonstrate that the combustion chamber average temperature and NO concentration decrease as the excess air factor increases for a given air mass flow. As the combustion air temperature increases, combustion chamber temperature increases and the NO concentration increases sharply.**

Combustion, simulation, burner, NOx emission.

I. Introduction

The degradation of the world fossil fuel reserves pushed several researchers to improve the performances of the energy systems for an effective and profitable use of these resources, without neglecting the environmental side of the problem.

The field of industrial combustion is very broad. In fact, burners constitute the most widely adopted alternative to convert fossil energy into thermal energy. This encouraged several authors Ladislav et al. [1] to optimize these burners to increase their combustion efficiency and to decrease their pollutant emissions. Faced with the complexity of the problem and industrial configurations, the use of CFD (Computational Fluid Dynamics) becomes essential to answer many questions. Computer simulation, Armand [2], has been employed to understand the thermal-flow and combustion phenomena in the industrial burners and furnaces to resolve operation problems and in search for optimal solutions. Marias et al. [3] have performed numerical simulations on a model of industrial burner. They studied the influence of the swirl number on pollutant emissions and the impact of the position of the injector and the opening of valves on the characteristics of the flow field. Because of the wide use of burners and furnaces in commercial and industrial facilities, there is a need for studies for better understanding of how and where NOx formation occurs in such furnaces. These studies are important for efficient and clean operation of utility kilns [4], for improving kilns/burner design, and for development of inferential methods for emission monitoring.

A fully three-dimensional flow, heat transfer and combustion computer model was developed by Boyd et al [5] for tangentially fired pulverized fuel furnaces. The complete model solves equations for gas momentum and mixing, particle trajectories and combustion and energy conservation with radiation transfer. Zheng et al. [6] presented numerical and experimental study on reduction of NOx emissions in the furnace of a tangentially fired boiler under different operating conditions using a simplified NOx formation mechanism model.

Other recent studies [7], [8] have involved the total flow and energy modeling of industrial gas furnaces. The focus in these studies was on improving the efficiency of furnaces and reducing NOx pollution among other considerations.

This paper presents the results of 3D computer simulation of the combustion chamber of a 80 KW burner to study NOx formation under various operating conditions of the burner. The formation of NOx in industrial kilns is a very complicated problem due to many parameters that influence its formation process. The numerical calculation of the combustion process in industrial kilns is a 3D problem that involves turbulence, combustion, radiation in addition to NO modeling. In the combustion chamber, the heat transfer is dominated by radiation. Hence accurate prediction of the radiative heat transfer is necessary to obtain a correct estimate of the thermal kilns performance.

Based on the above literature search, it is clear that the problem of NOx formation in industrial furnaces although received much attention in regard of coal fired kilns, a limited portion of research work was focused on gas fired furnaces. The present work is aimed at conducting a numerical investigation, of an industrial burner of a ceramic tunnel furnace, of the influence of the air to fuel ratio and the inlet combustion air temperature on NO formation.

II. Geometry

The tunnel furnace of SOMOCER with a length of 100 m includes about 40 burners with the same technical specifications. In this work, we are interested in studying one

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of its diffusion burners having a length of about 0.2 m (Fig. 1). The burner body includes air and natural gas inlets having diameter 0.03 m and 0.024 m respectively. Air enters the flame tube through a swirler including 24 blades at angles of 45°. The six gas nozzles have a diameter of 1 mm and are distributed in a symmetrical way on the swirler injection cone, separated by angles of 60°. The flame tube placed downstream of the swirler has a diameter of 0.062 m and length equal to 0.38 m. This tube leads to the combustion chamber of length, width and height, respectively, equal to 0.6x0.2x0.2 as shown in (Fig. 2).

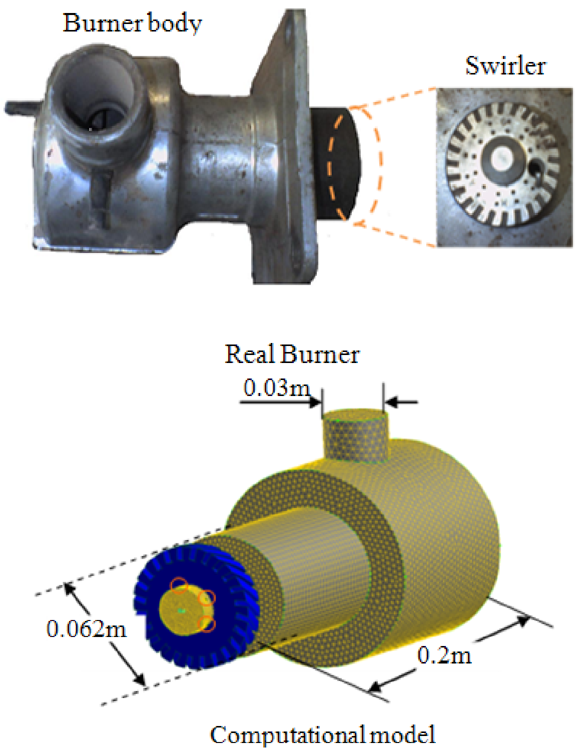

Fig. 1 Layout of the considered burner.

III. Mathematical Model

Since the flows in the combustor are turbulent and reactive, the Favre-averaged form of conservation equations is used in this study to account for the effects of density change. The steady three-dimensional conservation equations of mass, momentum, energy and species can be expressed as [9]:

$$\frac{\partial\,(\bar{\rho}\tilde{u}_i)}{\partial\, x_i} = 0 \tag{1}$$

$$\frac{\partial\left(\bar{\rho}\,\tilde{u}_j\,\tilde{u}_i\right)}{\partial\, x_j} = \frac{\partial}{\partial x_j}\left[\mu_e\left(\frac{\partial \tilde{u}_i}{\partial x_j}+\frac{\partial \tilde{u}_j}{\partial x_i}\right)-\left(\frac{2}{3}\mu_e\frac{\partial \tilde{u}_l}{\partial x_l}\right)\right]-\frac{\partial\,\bar{p}}{\partial\, x_i} \tag{2}$$

Where $\mu_e = \mu + \mu_t$, $\mu_t = \rho C\mu k^2/\varepsilon$ and $C_\mu = 0.09$.

$$\frac{\partial\left(\bar{\rho}\,\tilde{u}_i\,\tilde{h}\right)}{\partial\, x_i} = \frac{\partial}{\partial\, x_i}\left(\frac{\mu_t}{\sigma_h}\frac{\partial\,\tilde{h}}{\partial\, x_i}\right)+\tilde{S}_h \tag{3}$$

Where S_h consists of sources of enthalpy due to chemical reaction and radiation.

$$\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_j\tilde{Y}_i) = \frac{\partial}{\partial x_j}(\bar{\rho}D_i\frac{\partial \tilde{Y}_i}{\partial x_j} - \overline{\rho u_j'' Y_i''}) + \bar{R}_i \tag{4}$$

Where R_i is the net rate of production of species i.

Basically, turbulent models incorporated with the governing equations are used to determine the Reynolds Stresses. RNG turbulence model [10] was used to provide better results for vortex flows. In order to correctly predict the temperature distribution in the furnace a radiative transfer equation (RTE) for an absorbing, emitting and scattering medium was solved. The solution of the RTE for this application was obtained using the *Discrete Transfer* (DTRM) radiation model [11]. The *Eddy Dissipation* (ED) [10] combustion model is used to model turbulence-combustion interactions.

In this study, the combustion of methane (CH_4) is modeled by a one-step global reaction mechanism, assuming complete conversion of the fuel to CO_2 and H_2O. The complete stoichiometric combustion equation is given as:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

The methane-air mixture consists in four species (CH_4, CO_2, H_2O and O_2). The mixing and transport of chemical species is modeled by solving a single fuel mass fraction equation. The other species are determinate through the total mass conservation.

IV. NO_x Generation

The combustion process considered in the present study has two mechanisms for NOx formation. The first is the thermal NOx which is controlled by the nitrogen and oxygen molar concentrations and the temperature of combustion in excess of 1300 °C. The second is the prompt NOx which is formed from molecular nitrogen in the air combining with fuel in fuel-rich conditions. This nitrogen then oxidizes along with the fuel and becomes NOx during combustion. The mass transport equation for the NO species, including convection, diffusion, production and consumption of NO was solved. The mechanisms of NOx formation and correlations can be captured by mathematical models [8], and their dependence on furnace operating conditions and fuel composition. The Fluent simulation package provides state-of-the-art models for prediction of combustion and pollutant formation, including built-in NOx prediction. The NOx calculations are based on a model of NO emissions for furnaces by Li and Thompson [12]. The model is derived from the extended Zeldovich mechanism and requires only a few physical parameters obtained from experiments. The expressions for the reactions rate coefficients used in the NO model are given in Hanson and Salimian [13].

V. Boundary Conditions

The flow and thermal variables are defined by the boundary conditions on the boundaries of the studied model.
Mass-flow inlet conditions are applied at the two inlets in the burner. Out flow boundary condition is applied at the exit of the combustion chamber and the walls are treated as constant wall temperature. The walls are stationary with no-slip conditions applied on the wall surface. The detailed and typical data boundary conditions are summarized in the Table I below.

Table.I Boundary conditions.

	Type	*Values*
Air inlet	*Mass Flow inlet*	**Q**=0.0084 [Kg/s], **T**=370[K], $\mathbf{D_h}$=0.03[m] and $\mathbf{I_t}$=10%
Fuel inlet	*Mass Flow inlet*	**Q**=0.000485 [Kg/s], **T**=310[K], $\mathbf{D_h}$=0.024[m] and $\mathbf{I_t}$=10%
Walls of combustion chamber	*Wall*	**T**=400[K]
Flame tube	*Wall*	**T**=320[K]
Combustion chamber exit	*Out flow*	---

The specific heat of the species is temperature and mixture dependant. The physical properties are defined for the mixture material and the constituent species.

VI. Grid and Computational Methodology

The computational mesh of the geometrical model was created in GAMBIT 2.2.30 [11] (see Fig. 2). Tetrahedral mesh elements were applied around more complicated features such as fuel nozzles while hex/wedge mesh elements were used elsewhere. The entire mesh consists in about 420,000 cells. The mesh surrounding the nozzles and flame area is finer in order to help resolve the expected large gradients of the independent variables. On the other hand, the remainder of the combustion chamber was meshed with coarser mesh cells as no significant gradients were expected here.

Solution of transport equations is achieved using the commercial CFD software FLUENT version 6.2.16 [11] using its built-in sub models and algorithms. The mathematical model is discretized using the finite volume technique in a 3D- staggered grid. Central differences are employed for the evaluation of diffusion terms, while a second order Upwind scheme is used for the evaluation of the convective one. A time-marching SIMPLE [12] algorithm is employed to couple velocity-pressure fields. Discretized equations are solved in a segregated manner using a multigrid solver. The convergence time-marching iterative procedure is truncated once normalized residuals are below 10^{-6}.

VII. Results and Discussion

This study illustrates the analysis of combustion simulation. The influence of the different operating conditions, the inlet combustion air temperature and the fuel to air ratio (by varying fuel mass flow at fixed air mass flow rate), on the maximum and average temperature inside the combustion chamber as well as the temperature and NO concentration at the exit of the chamber.

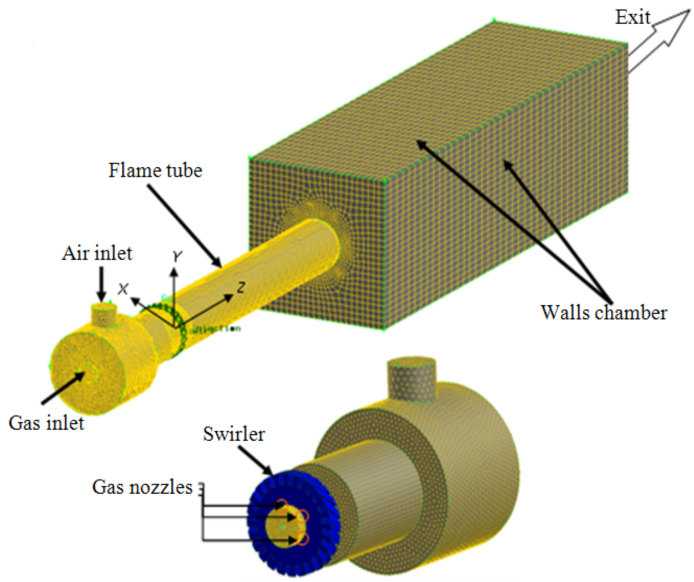

Fig. 2 Computational model of the studied burner showing different sections with meshes.

The mass-averaged value was used to present the average temperature. Those operating conditions are given in the following (Table II).

Table II Operating conditions

Parameter (changed)	**Parameter (fixed)**
Temperature (K)	*Excess air factor*
370	1
470	
570	
670	
870	
Excess air factor	*Temperature (K)*
0.9	370
1	
1.15	

A. Influence of air to fuel ratio

The studied cases consider change of air to fuel ratio at a fixed air mass flow rate. For these cases, the mixture was kept at real operating conditions at all the considered values of fuel to air ratio. Fig. 3 shows the influence of the air to fuel ratio at a fixed air mass flow rate on the temperature distributions. The air to fuel ratio is expressed in terms of the excess air factor. The excess air factor is defined as the air to fuel ratio divided by the theoretical value. It is shown that although the combustion chamber maximum temperature is almost fixed, the average furnace temperature as well as the exit temperature decrease as the A/F ratio increases. As the air flow rate is increased above the theoretical value, the burner input energy per kg of flue gases is reduced and, thus, the exhaust gas temperature decreases.

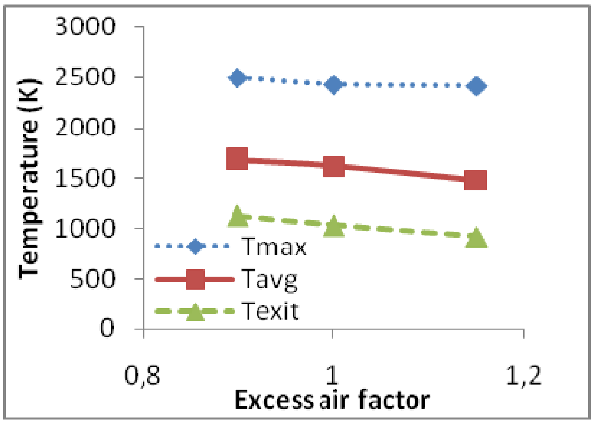

Fig.3 Influence of Air/Fuel ratio on the temperature profiles

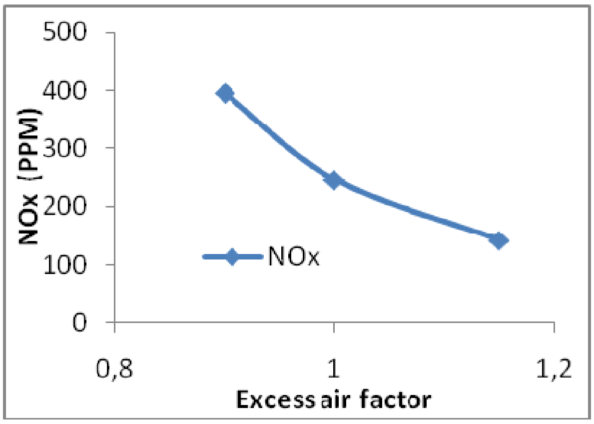

Fig.4 Influence of Air/Fuel ratio on the NO profile

Fig. 4 shows the influence of the air to fuel ratio on the NO distribution. This results provide that the NO concentration decreases as the air to fuel ratio increases for a given air mass flow rate. The NO concentration is proportional to the temperature which exhibits continuous decrease with air to fuel ratio as shown in Fig. 3. Moreover, Figs. 4 show that the NO concentration decreases monotonically with the air to fuel ratio.

B. Influence of combustion air temperature

The influence of combustion air temperature on the temperature distributions is shown in Fig. 5. As the inlet combustion air temperature increases, the combustion chamber maximum temperature increases. The average temperature increases up to T = 470 K but shows a decrease at T = 570 K and continue to increases at higher combustion air temperatures. The exhaust temperature shows a minimum value at combustion air temperature of 370 K. It increases up to T = 470 K and still almost fixed for higher combustion air temperatures.

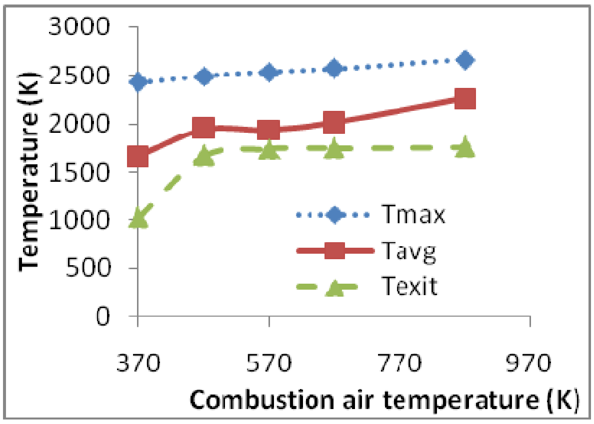

Fig.5 Influence of combustion air temperature on the temperature profiles

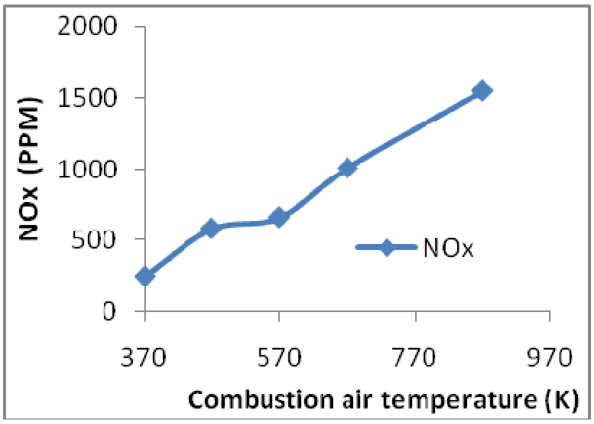

Fig.6 Influence of combustion air temperature on the NO profile

On Fig. 6 we present the influence of the combustion air temperature on the NO distribution. It is show that the NO concentration increases with increased combustion air temperature. As well as it is known that NO increases with temperature. As the combustion air temperature increases, and furnace temperature increases and NO concentration increases. It also appears that the NO formation is highly dependent on temperature. In fact, the NOx production rate increases for about 300 PPM for every 100 K temperature increase.

VIII. CONCLUSION

In this work, we performed numerical simulations of an industrial burner. Simulations were carried out using the commercial code FLUENT. The discussion focused on the problem of NOx pollution by providing the influence of different operating conditions on temperature and NO distributions. The obtained results demonstrate that the combustion chamber average temperature and NO concentration decrease as the excess air factor increases for a given air mass flow. As the combustion air temperature increases, combustion chamber temperature increases and the NO concentration increases sharply.

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