ON THE IMPROVEMENT OF THE COMBUSTION PROCESS AIMING POLLUTANTS EMISSIONS DECREASE

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ABSTRACT

One of the challenges of the combustion process refers to the production of carbon monoxide and its sedimentation on coils and furnace walls. This phenomenon decreases the heat transfer efficiency of the furnace. In this paper, an industrial furnace faced with incomplete combustion is investigated. The orifice diameter, the fuel per oxygen ratio, and the velocity of the fuel jet are the parameters investigated. The simulation results show that the decrease of the flame length increases the maximum temperature of the flame and decreases the carbon monoxide production rate. In other words, the decrease of the flame length leads to decrease of the carbon monoxide mole fraction; however, the nitrogen oxides production rate increases. In addition, it is observed that the orifice diameter has the maximum effect on the combustion process efficiency. The lowest diameter (0.5 mm) is selected as the optimum diameter, while $CH_4/O_2 = 0.25$ is chosen as the optimum value of the fuel/O_2 ratio. The effects of the other parameters on the combustion process are negligible.

Keywords: *combustion, flame, carbon monoxide, NOx, temperature.*

INTRODUCTION

Burners are one of the important structural elements of an industrial furnace. They have various components including the fuel intake, the torch box and the burner chamber. In practice, the flame, its uniformity, length, and color affect the efficiency of the combustion process. The flame is expected to extend along the furnace excluding any contact with its walls or pipes, because of creation of hot spot points [1]. The formation of coke during the combustion process, its sedimentation on the coil and the furnace walls decreases the efficiency of the heat transfer and the combustion process. Many studies are carried out on burners aiming to improve their performance. They refer to various parameters such as the mechanical structure of the torch, the means of fuel and air introduction, and the corresponding operating conditions. It is shown that the control of the flame, either by changing the structure of the burner or using operational parameters, can decrease the carbon monoxide amount produced in the furnace [2 - 4]. Due to the fact that a torch application is not always possible, the modification of the system's operating conditions becomes more important.

The present communication describes a two-dimensional simulation of an industrial furnace burner developed numerically. It aims at the improvement of the combustion process and the operational parameters affecting the decrease of carbon monoxide and NOx emissions production. A single burner is used.

Geometry

The simulated burner consists of two main parts: a nozzle section and a reaction section. In the present two-dimensional simulation, the gas nozzle is considered as a single nozzle. The reaction section has dimensions of 3 cm × 8 cm, while the nozzle section is 1 cm × 1 mm. Fig. 1 illustrates the burner's geometry and the related boundary conditions. Methane as a feed is injected to the combustion chamber through a nozzle by a velocity of 80 m/s, while, the velocity of the air is 3 m/s. The properties of a real plant burner are presented in Table 1.

In order to obtain grid independency results, different uniform grid numbers of 40000, 50000 and 60000 are examined. It is observed that the difference between the carbon monoxide mole fraction at the furnace outlet based on 50000 grids and 60000 grids is insignificant (< 1 %). The carbon monoxide mole fraction is 0.532, 0.464 and 0.459 for grids of 40000, 50000 and 60000, respectively. The mesh number of 50000 grids is used for the results generation.

Governing equations

The continuity equation, the momentum, the heat transfer, the mass transfer and the chemical reactions equations are required for the combustion process simulation. The corresponding governing equations are given as follows [5]:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0. \quad (1)$$

$$\rho \frac{\partial u}{\partial t} + \rho(\nabla.u)u = \nabla.[\mu(\nabla u + (\nabla u)^T] +$$

$$+ \rho g + \rho g \beta(T - T_0), \quad (2)$$

where μ is the viscosity, while β is the thermal expansion coefficient.

The energy conservation equation refers to (Bird et al., 2002):

$$\rho Cp \frac{\partial T}{\partial t} + \rho Cpu.\nabla T = \nabla.(K\nabla T), \quad (3)$$

where ρ is the density, Cp is the heat capacity, T is the temperature, u is the velocity, while K is the thermal conductivity.

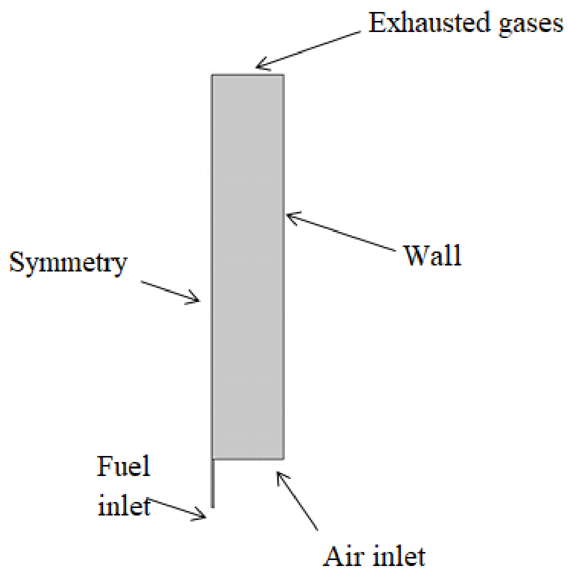


Fig. 1. Geometry and related boundary conditions of a burner.

The mass conservation equation is presented by Bird et al. [5]:

$$\vec{u}\nabla c = D\nabla^2 c \quad (4)$$

where c is the concentration, while D is the diffusivity.

Pure methane is the fuel considered for the combustion. The chemical reactions related to the combustion process refer to:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (5)$$

$$CH_4 + O_2 \rightarrow CO + H_2O \quad (6)$$

$$CO + O_2 \rightarrow CO_2 + H_2 \quad (7)$$

$$N + O_2 \rightarrow 2NO \quad (8)$$

Table 1. Properties of a real plant burner.

parameter	Real plant data
Nozzle diameter [mm]	1
Fuel jet velocity [m/s]	80
Air velocity [m/s]	3

Table 2. Comparison of simulation results with experimental data

component	Real plant data	Simulation results	Unit	Error (%)
CO	0.450	0.455	mol/lit	-1.112
CO_2	0.415	0.393	mol/lit	5.301
NO	0.456	0.449	ppm	1.535

In order to verify the validity of the simulations, the results are compared to real plant data of a gas refinery. Table 2 illustrates the juxtaposition of the simulation results and the experimental data. It is seen that the average error is 2.65 %; therefore, according to the accuracy of the results obtained, the simulation carried out can be used to optimize the combustion process.

RESULTS AND DISCUSSION

According to the variation of the designed operating parameters, the efficiency of the combustion process decreases, the burning of the fuel is incomplete, while the production rate of carbon monoxide increases. Therefore, the present study focuses on several parameters including the orifice diameter, the fuel/air ratio, and the fuel injection velocity.

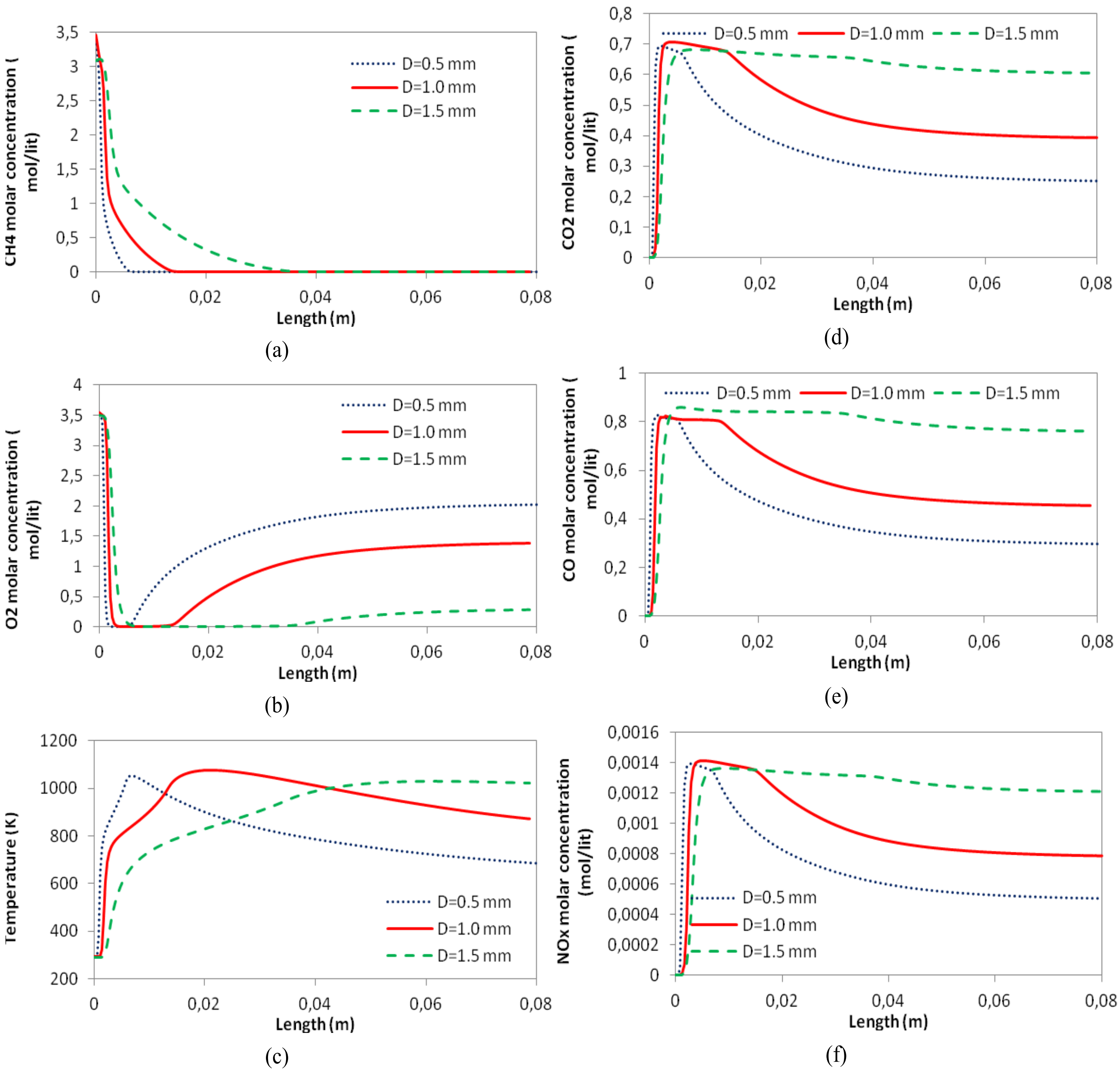


Fig. 2. An effect of the orifice diameter change on (a) the methane concentration profile, (b) the oxygen concentration profile, (c) the temperature profile, (d) the carbon dioxide concentration profile, (e) the carbon monoxide concentration profile, (f) NOx concentration profile.

Eeffects of the orifice diameter on the combustion process

In order to investigate the effect of the orifice diameter on the quality of the combustion, three diameters of 0.5 mm, 1.0 mm, 1.5 mm, are investigated.

Fig. 2 illustrates the effect of the diameter of the fuel nozzle on the concentration of the components and the temperature profile. It is shown that the methane profile is extended forward and its concentration reaches zero at a longer length by increasing the orifice diameter. For instance, the methane concentration reaches a value of zero at 0.5 cm and 1.2 cm when the nozzle diameter is equal to 0.5 mm and 1.0 mm, respectively. The comparison of the methane and the oxygen profiles (Fig. 2(b)) shows that the oxygen consumption rate decreases with increase of the orifice diameter. This leads in turn to the forward extension of the flame. Fig. 2(c) illustrates the temperature distribution based on the orifice diameter. It is seen that the increase of the diameter leads to an initial maximum temperature increase which is then followed by a decrease, i.e. the maximum temperature refers to 1019°C, 1063°C, and 1014°C for diameters of 0.5 mm, 1 mm, and 1.5 mm, respectively. The comparison of the maximum point's values of carbon dioxide production

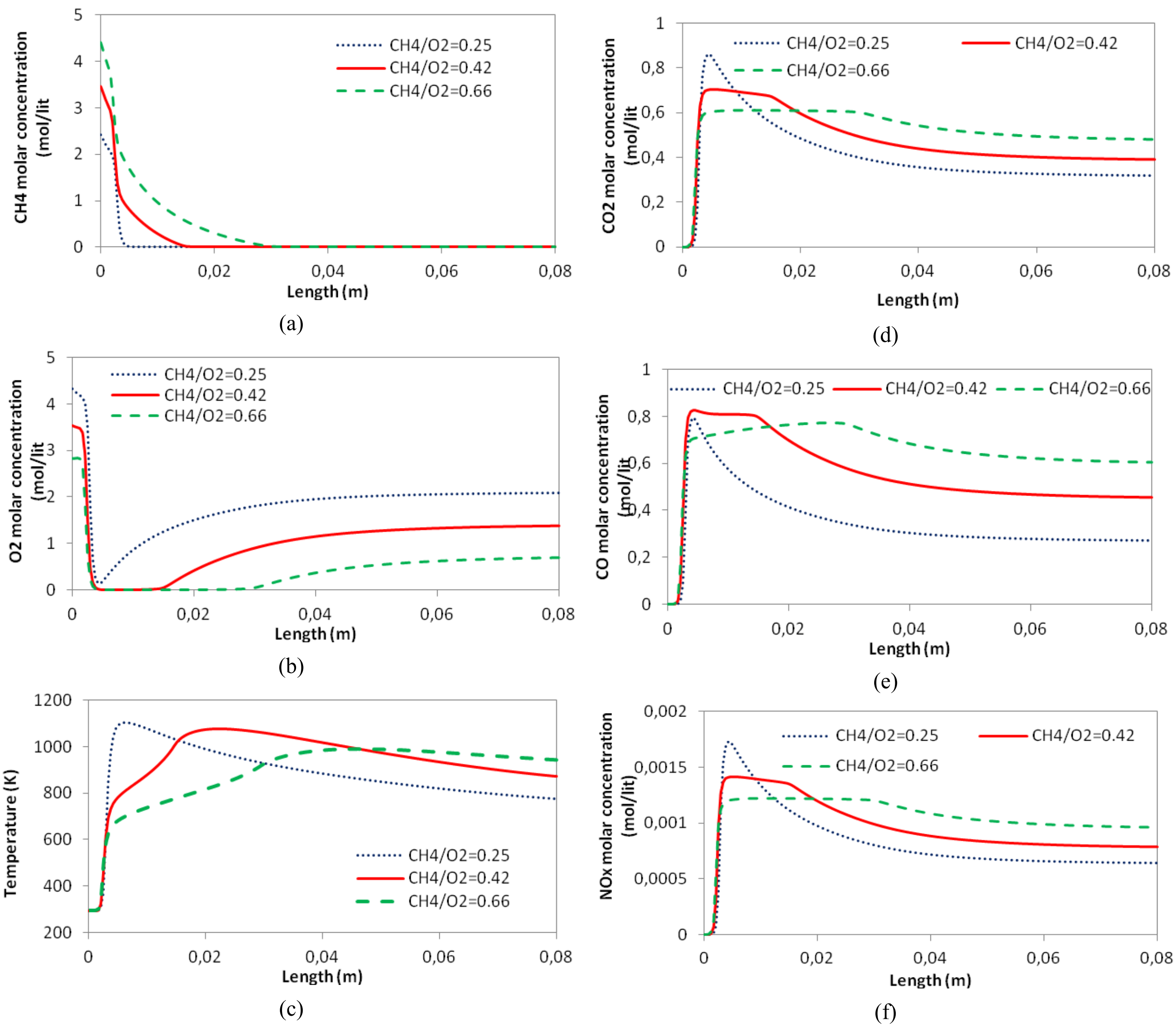


Fig. 3. An effect of the fuel/air ratio on (a) the methane concentration profile, (b) the oxygen concentration profile, (c) the temperature profile, (d) the carbon dioxide concentration profile, (e) the carbon monoxide concentration profile, (f) NOx concentration profile.

(Fig. 2(d)) shows that the diameter increase results in an initial increase of carbon dioxide emissions, which is then followed by a decrease. The adverse rate is shown for carbon monoxide emissions. In fact, the quality of the combustion process increases and the methane burning improves with maximum temperature decrease. In addition, NOx production decreases (Fig. 2(f)) in case of uniform temperature distributions. It is noted that NO concentration is used in this study to stand for NOx concentration because of its highest value among those of the other nitrogen oxides. The trend of the temperature profiles are in the line with those in the literature [3, 6, 7].

Eeffects of the fuel/air ratio on the combustion process

Fuel/air ratios of 0.25, 0.42 and 0.66 are investigated aiming to follow the fuel/air ratio effect on the burning, its products and the temperature in the furnace. Fig. 3 shows the effect of the fuel/air ratio on the concentration of the components and the temperature profile. It is seen that when the ratio of methane to oxygen is reduced from

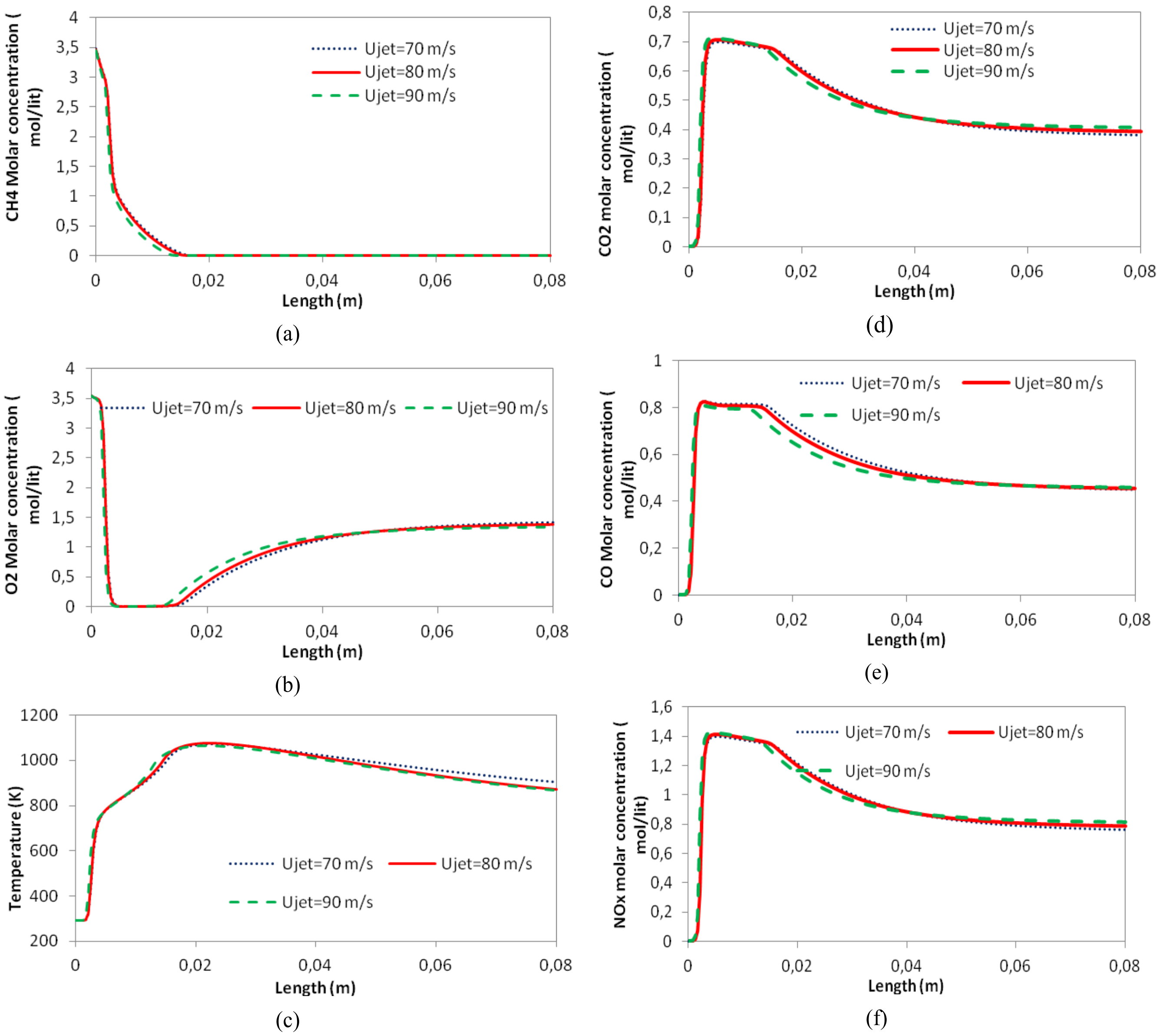


Fig. 4. An effect of the fuel jet velocity on (a) the methane concentration profile, (b) the oxygen concentration profile, (c) the temperature profile, (d) the carbon dioxide concentration profile, (e) the carbon monoxide concentration profile, (f) NOx concentration profile.

0.42 to 0.25, the methane burning reaction occurs within a shorter interval. In fact, the oxygen is still available for the reactions proceeding but the burning takes place in a shorter time period, i.e., when the ratio of methane to oxygen is decreased from 0.42 to 0.25, the flame length decreases from 0.015 m to 0.005 m. As it is seen, an increase of the methane to oxygen ratio increases the flame length and the combustion process occurs more slowly. In fact, the lack of oxygen causes a further expansion of the flame, while the maximum temperature, the carbon dioxide production rate, and consequently the burning quality decrease. This in turn results in NOx production rate decrease and carbon monoxide production rate increase. So, the lack of oxygen provides combustion occurring in a wider time interval and a lower ignition rate. Therefore, the CO_2 profiles have a smaller maximum. The limited access to oxygen causes incomplete combustion of methane and increases CO production.

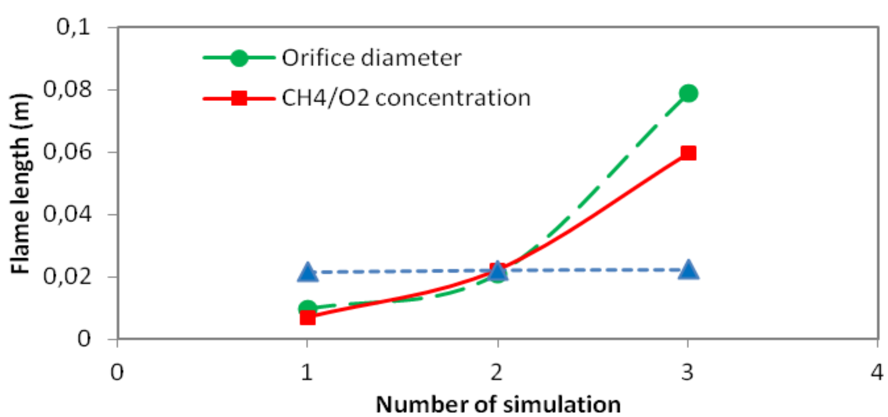
Effects of the fuel jet velocity on the combustion process

The fuel jet velocity of 70 m/s, 80 m/s and 90 m/s are studied aiming to evaluate the effect of the fuel jet velocity at a constant flow rate on the fuel products and the flame temperature. Fig. 4 shows the effects of the jet velocity on the concentration of the components and the temperature profile. As it is seen, the variation of the fuel jet velocity has a negligible effect on the methane combustion and the flame length.

The flame length in each simulation

Fig. 5 shows the effect of the different parameters evaluated in the study on the flame length. The latter has a significant impact on the temperature distribution and the pollutants emissions. It is evident that the effects of the variation of the orifice diameter and the fuel to air ratio are more significant than that of the fuel jet velocity, i.e. the increase of the orifice diameter from 0.5 mm to 1.5 mm results in a flame length increase from 0.01 m to 0.08 m. In fact, the flame length depends on methane, carbon monoxide, and carbon dioxide concentration curves, as well as the temperature distribution curve. When the combustion takes place in case of a shorter flame length, the maximum temperature of the flame increases which leads to a decrease of carbon monoxide concentration, while that of nitrogen oxides increases.

The literature review provides various methods of pollutants production control. One of the most common methods is to premix fuel and air prior to the introduction to the combustion chamber [8, 9]. Another possibility refers to the improvement the furnace efficiency through enhancement of the heat transfer radiation by coils. In this case, the transferred heat decreases the maximum temperature, which in turn means that more heat is transferred but the flame temperature is lower [10] and consequently NOx production is lower. The use of a porous burner is another way of NOx decrease [4]; however, the production of coke increases the possibility of barring the porous media. The results of this



Number of simulation	Fuel/air ratio	Diameter of orifice (mm)	Fuel jet velocity (m/s)
1	0.25	0.5	70
2	0.42	1.0	80
3	0.66	1.5	90

Fig. 5. A flame length dependence on the orifice diameter, the fuel/air ratio, and the fuel jet velocity.

study show that the variation of the operating condition referring to the flame length control leads to a decrease of the emitted pollutants. Due to the fact that there is no chance to change the overall structure of the furnace in the existing industrial unit, the changes of the inlet diameter, the fuel/air ratio, and the fuel flow rate are studied. It is observed that by changing the diameter of the fuel orifices and the fuel/air ratio the pollutants emission produced in the furnace decreases.

CONCLUSIONS

The present investigation is focused on the improvement of the combustion process in order to decrease the pollutants emission. The effects of the orifice diameter, the fuel/air ratio, and the velocity of the fuel jet are evaluated. It is shown that the flame extension decreases the maximum temperature and provides a uniform distribution of the temperature along the furnace. It also prevents the appearance of hot spot points on the walls of the furnace and the coils and decreases NOx production. However, the temperature decrease causes an increase of CO production and incomplete combustion. It is observed that the decrease of the orifice diameter and the fuel/air ratio shorten the flame length decreasing CO production and increasing that of Nox. The increase of the velocity of the fuel jet increases slightly the flame length and, as a result, increases CO production and decreases that of Nox.

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