Open Journal of Applied Sciences, 2018, 8, 203-210
http://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Computer Analysis of a Methane Fired Crucible Furnace

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How to cite this paper: Santiago, F., Barron, M.A., Hilerio, I. and Medina, D.Y. (2018) Computer Analysis of a Methane Fired Crucible Furnace. *Open Journal of Applied Sciences*, **8**, 203-210.
https://doi.org/10.4236/ojapps.2018.86017

Received: May 16, 2018
Accepted: June 23, 2018
Published: June 26, 2018

Abstract

Two design factors and one operation parameter of a methane fired crucible furnace are numerically explored in this work. These are the number of burners, the location of the exhaust gas exit, and the air-fuel ratio, respectively. Three dimensional steady state Computational Fluid Dynamics simulations are carried out in order to analyze the influence of the above factors on the mean cavity temperature in absence of thermal load, the methane content and the oxygen content of the exit gas.

Keywords

Air-Fuel Ratio, Computational Fluid Dynamics, Crucible Furnace, Exit Gas Composition, Mean Temperature, Numerical Simulations

1. Introduction

Crucible furnaces are frequently used at foundry industry to melt charges of ferrous and nonferrous metals. The charge is placed inside a refractory crucible and is heated and melted by thermal conduction through the crucible walls [1]. In turn, the crucible walls are heated by fuel (gas, oil, coke) or electricity (resistive heating). Sometimes, the charge is directly heated by electrical induction. Unfortunately, four major problems in fuel heated furnaces arise: non-uniform flame distribution, oxidation of metal, scale formation and emission of pollutants [2].

More and more frequently, computers and software are employed to analyze, optimize and design fuel fired furnaces [3]. For example, [4] reported the design of fume extraction hoods for smelting vessels using a combination of engineering and Computational Fluid Dynamics (CFD) modeling. CFD analysis of a new hood showed a significant improvement in fume capture. Construction and installation of the hood was performed and a 65% reduction in fume emission is reported. In [5], a three dimensional (3D) CFD simulation with experimental validation of a gas fired self-regenerative crucible furnace is presented.

A study, both experimental and numerical, of temperature distribution during oscillating combustion in a crucible furnace is presented in [6]. The authors found that enhanced heat transfer rate, reduced processing time and increased furnace efficiency with visibly clean emissions are obtained when the conventional combustion mode is replaced by the oscillating combustion mode. In [7] the simulation of thermal analysis of fuel fired crucible furnace to predict the effect of thermal stress and strain on it is studied using commercial simulation software. Here, the layers of the furnace walls having different materials with different thermal coefficient of expansion are considered. A report focused on the application of CFD modeling to solve challenging ventilation problems during metallurgical industrial process events, such as fume capture in furnaces, is presented in [8]. Some case studies in which various heat and fume sources with complicated geometry and interaction of natural buoyancy are discussed by the authors.

In this work, two design and one operation factors of a methane fired crucible furnace are numerically explored: the location of the exhaust gas exit, the number of burners, and the air-fuel ratio. 3D steady state CFD simulations were carried out in order to analyze the influence of the above factors on the mean cavity temperature, and the methane and oxygen contents in the exit gas.

2. Mathematical Model and Its Numerical Solution

The combustion gases flowing inside the furnace cavity, *i.e.* the space between the external walls of the furnace and the crucible, are considered Newtonian fluids, and their momentum balance is represented here by the Navier-Stokes equations [9]. Besides, the mass balance and the heat balance are modeled through the continuity equation and the energy equation, respectively [9]. Turbulence in the furnace cavity is simulated by means of the classical two equations K-ε model [10]. The 3D steady-state versions of the momentum, mass and heat balances were numerically solved using commercial CFD software [11]. The computational mesh employed in the computer simulations for a crucible furnace with two burners and lateral gas exit is shown in **Figure 1**. This mesh is composed of 1,001,367 tetrahedral/hybrid cells, and the PRESTO (Pressure Staggering Option) scheme is selected for the discretization of the continuity balance. For the pressure-velocity coupling, the PISO (Pressure Implicit with Splitting of Operators) algorithm was employed [11].

3. Computer Simulations

In the computer simulations the dimensions of the crucible were as follows: height = 0.8 m, lower diameter = 0.4 m, upper diameter = 0.7 m, which approximately correspond to a 20 kg aluminum furnace [12]. The dimensions of

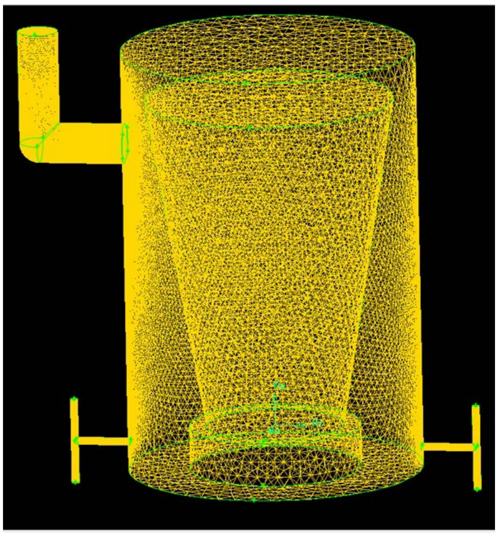

Figure 1. 3D mesh of a crucible furnace with two burners and lateral gas exit.

the combustion chamber, *i.e.* the furnace external cavity or simply the cavity, were as follows: height = 1.0 m, external diameter = 0.7 m, gas exit diameter = 0.1 m, burner diameter = 0.025 m. Two locations for the exhaust gas exit were considered: top, and lateral. The fuel was methane gas.

Three values of the air-fuel ratio (AFR) were considered: 5, 9.5 and 15. These values approximately correspond to incomplete, stoichiometric and lean combustion, respectively [13]. An AFR value of 15 represents 58% of excess air. The exact AFR value which corresponds to the theoretical air for methane combustion is 9.52. Volumetric flow rates were 4.6633×10^{-3} and 4.9087×10^{-4} m^3N/s for air and methane, respectively. Both methane and air were tangentially fed into the burner at 300 K, and a premixed combustion system is considered. The air-fuel mixture was tangentially injected into the combustion chamber with an angle of 45 degrees in order to avoid the direct contact of the flame with the crucible walls.

4. Results and Comments

From now on, just steady state computer results are presented. **Table 1** shows the average temperature in the furnace external cavity in absence of thermal load as function of the number of burners, the location of the exhaust gas exit, and the air-fuel ratio (AFR). According to **Table 1**, the highest temperature (2700.27 K) is achieved with the one burner—lateral gas exit − AFR = 9.5 configuration. On the other hand, the lowest temperature (1928.15 K) is achieved with the two burners—top exhaust gas exit − AFR = 15 configuration. Generally speaking, the two burner configurations exhibit noticeable lower average temperatures than that corresponding to the one burner configurations.

Methane content in the exhaust gas in mole percent for the different furnace configurations is shown in **Table 2**. Given that the AFR value corresponding to the theoretical air for methane combustion is 9.52, AFR values of 5 and 9.5 emit unburnt methane. As expected, the methane content decreases as the AFR is increased, irrespective of the number of burners or the exhaust gas exit location.

Table 3 shows the oxygen content in mole percent in the exit gas. Given that AFR values of 5 and 9.5 are below the theoretical AFR value of 9.52, they provide less oxygen than that required for complete combustion of methane and, therefore, the oxygen content of their gas is null.

In Figures 2-5 are depicted the path of the combustion gases inside the furnace cavity for the several configurations considered in the computer simulations. Figure 2 and Figure 3 show the numerical results for the one burner configuration, with top and lateral fume exit, respectively. Figure 4 and Figure 5 show the numerical results for the two burners configuration with top and lateral fume exit, respectively. It can be observed that the air-fuel mixture is tangentially injected into the furnace cavity in order in flame does not hit directly the crucible bottom. The combustion gases ascend elliptically through the furnace cavity and they are headed towards the corresponding exhaust gas exit.

Observing the paths of the combustion gases for the two burner configurations depicted in Figure 4 and Figure 5, it can be noted that the individual paths from each burner collide and exhibit a perceptible short circuit. This phenomenon is appreciated in Figure 6, which shows a transverse view of the path of the combustion gases for a configuration with two tangential burners and top gas exit. Maybe the short circuit phenomenon is responsible of the lower average temperatures reported in Table 1.

Table 1. Average cavity temperatures (K) in absence of thermal load as function of number of burners, exhaust gas exit location and air-fuel ratio (AFR).

Number of burners, exhaust gas exit location	AFR = 5	AFR = 9.5	AFR = 15
1 burner, top	2482.43	2699.16	1935.94
1 burner, lateral	2483.67	**2700.37**	1938.10
2 burners, top	2472.83	2684.60	1928.15
2 burners, lateral	2475.19	2687.19	1929.67

Table 2. Methane content (mole %) in the exit gas as function of number of burners, exhaust gas exit location and air-fuel ratio (AFR).

Number of burners, exhaust gas exit location	AFR = 5	AFR = 9.5	AFR = 15
1 burner, top	8.00	0.12	0.00
1 burner, lateral	8.03	0.13	0.00
2 burners, top	8.03	0.15	0.00
2 burners, lateral	8.03	0.15	0.00

Table 3. Oxygen content (mole %) in exhaust gas as function of number of burners, exhaust gas exit location and air-fuel ratio (AFR).

Number of burners, exhaust gas exit location	AFR = 5	AFR = 9.5	AFR = 15
1 burner, top	0.00	0.00	5.27
1 burner, lateral	0.00	0.00	6.90
2 burners, top	0.00	0.00	6.93
2 burners, lateral	0.00	0.00	6.93

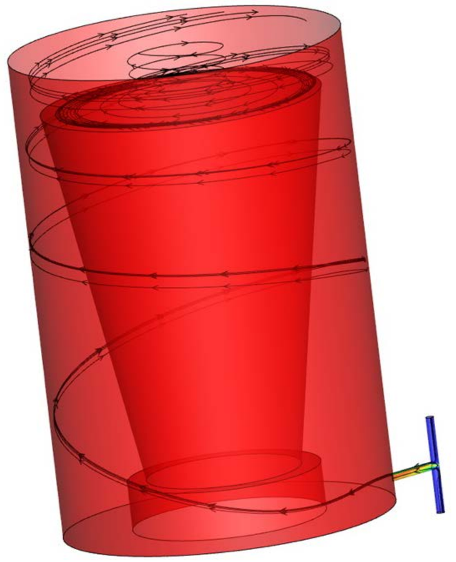

Figure 2. Path of the combustion gases inside the furnace cavity for a configuration with one tangential burner and top exhaust gas exit.

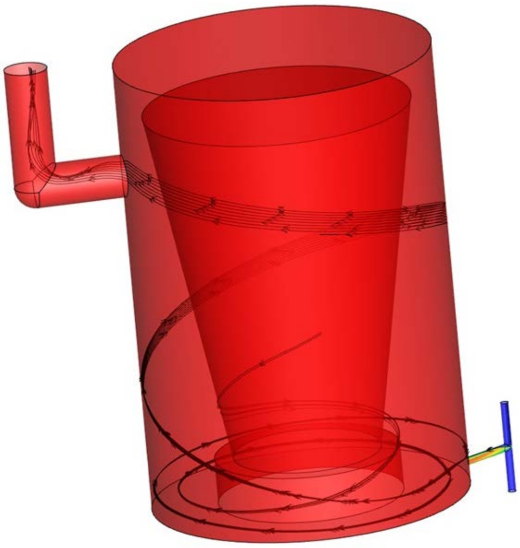

Figure 3. Path of the combustion gases inside the furnace cavity for a configuration with one tangential burner and lateral exhaust gas exit.

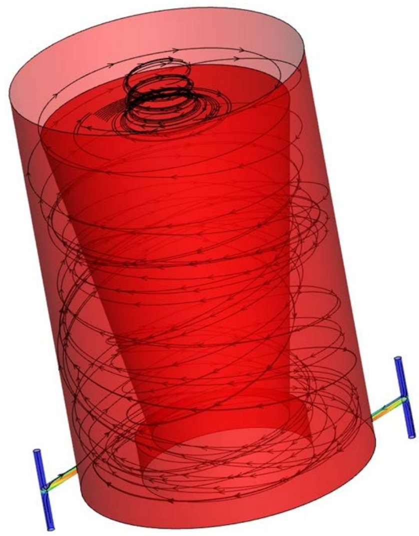

Figure 4. Path of the combustion gases inside the furnace cavity for a configuration with two tangential burners and top exhaust gas exit.

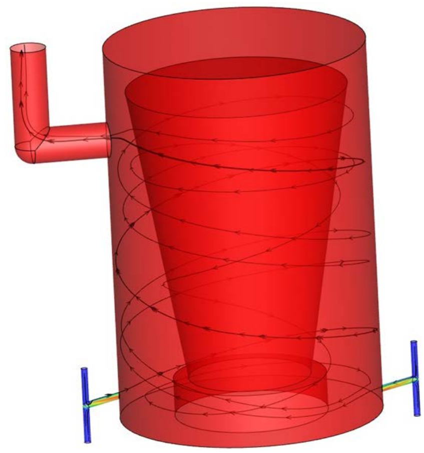

Figure 5. Path of the combustion gases inside the furnace cavity for a configuration with two tangential burners and lateral exhaust gas exit.

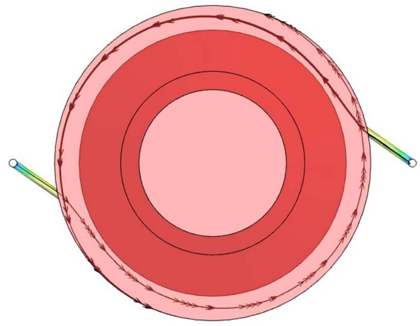

Figure 6. Transverse view of the path of combustion gases inside the furnace cavity for a configuration with two tangential burners and top exhaust gas exit.

5. Conclusions

The influence of some design and operating factors of a methane fired crucible furnace on average internal temperatures and exhaust gas composition were numerically studied using 3D Computational Fluid Dynamics (CFD) simulations. One and two burner configurations, top and lateral location of the exhaust gas exit, and air-fuel ratio (AFR) were considered those factors. The following conclusions arise from the computer results:

1) The one burner, lateral exhaust gas exit and AFR = 9.5 configuration yields the highest average internal temperature.
2) The lowest average internal temperatures are achieved with the two burner configurations, irrespective of the number of burners or the exhaust gas exit location.
3) The paths of the combustion gases for the two burner configurations collide and exhibit a short circuit. This short circuit phenomenon can be responsible of the low average temperatures reported for these configurations.

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