Numerical Study of a Tangentially Fired Boiler for Reducing Steam Tube Overheating

Guangwu Tang

Center for Innovation through Visualization and
Simulation,
Purdue University Calumet
2200 169th Street
Hammond, IN, 46323
219-671-3423 Email: tang@purduecal.edu

Kurt Johnson

ArcelorMittal,
Global Research and Development,
3001 E. Columbus Drive,
East Chicago, IN, 46312
219-399-6513 Email: Kurt.Johnson@arcelormittal.com

Dong Fu

Center for Innovation through Visualization and
Simulation,
Purdue University Calumet
2200 169th Street
Hammond, IN, 46323
219-989-3157 Email: fudong1985@gmail.com

Bin Wu

Center for Innovation through Visualization and
Simulation,
Purdue University Calumet
2200 169th Street
Hammond, IN, 46323
219-801-5397 Email: bin.wu@purduecal.edu

Albert Kirk

ArcelorMittal-Burns Harbor,
250 U.S. 12,
Burns Harbor, IN, 46312
219-787-3446 Email: Albert.Kirk@arcelormittal.com

Chenn Q. Zhou (Corresponding Author)

Center for Innovation through Visualization and
Simulation,
Purdue University Calumet
2200 169th Street
Hammond, IN, 46323
219-256-2665 Email: czhou@purduecal.edu

Abstract: A comprehensive numerical and experimental study on a 200 MW tangentially fired boiler firing metallurgical gases was conducted. A three-dimensional Computational Fluid Dynamics (CFD) model was developed to simulate the flow characteristics and combustion process inside the boiler. The Eddy Dissipation Concept combustion model was applied to take into account detailed turbulent interactive reacting chemical reactions. Field experiments were also conducted on the original tangentially fired boiler under different operation conditions. Flame profiles videos were captured during experiments. A quick comparison of the experimental flame profile with numerical simulation results shows good agreement. Wall steam tubes overheating problem was observed, and the hot spots were identified based on a wide range of typical operation conditions. The effect of total fuel input and natural gas percentage on the furnace wall temperature were investigated.

Key Words: CFD, Tangentially Fired Boiler, Metallurgical Gases, Temperature Deviation.

1 Introduction

Tangential fired boilers are widely used in modern industrial plants mainly for steam generation. Tangential fired boiler is also called corner-fired furnace [1], which is determined by its furnace shape and the position of the fuel/oxidizer inlet. It is normally with four sides and four corners where the fuel and air are supplied. During operation, the flames are directed tangentially connected and there is an imaginary circle in the center of the boiler created by the flow vortex [2]. The inside combustion with high temperature can dramatically expand the gas volume and lead the flue gas moving upwards with vortex combustion characteristics.

The advantages of using tangential fired boilers are obvious, such as good flame stability, good adaptability to different kinds of fuels and low NO_x emissions [3,4]. However, there is a frequently reported problem of steam tube rupture. It is believed that the heat imbalance and gas temperature deviation both in the vertical combustion zone and the horizontal flue gas pass way are the main reasons caused the local overheating and steam tube failure with vapor leakage accidents on the wall [5]. In order to alleviate the steam tube overheating problem, further studies on the tangentially fired boilers are needed. Physical experiment method was an old but practical way engineers used to do to get better understanding of the boilers, but full scale measurements are restricted by the high risk and cost [6]. Collaborating with physical experiments, the numerical methods can help to conduct computational experiments effectively and safely.

Computational Fluid Dynamics is a process of replacing the complex Partial Differential Equations (PDEs) that govern the flow and reactions with a simpler system of algebraic equations, and then do calculations on the large amount of divided cells in a domain through iterations refer to boundary conditions. The CFD models can conduct experiments on computer at different operation conditions, and can help visualize the results both statistically and graphically [6-8]. Many researchers conducted numerical simulation on industrial tangentially fired boilers. Yuegui Zhou, et al [3,4, 9] studied the flow field in the upper furnace of a large scale tangentially fired boiler, they found that the flow field was apparently different on the left and right side of the upper part and the velocity deviation is large in horizontal flue gas pass, which was the main reason caused the operational accidents of large scale tangentially fired boilers, such as steam tube overheating and explosion of super heaters. Yin, et al [10] studied the flow, combustion, heat transfer and

emissions of a 609 MW utility tangentially fired boiler by CFD and showed good agreement with design parameters and site operation records. Vuthaluru et al [11] modeled a large scale tangentially fired boiler by using CFD to predict the temperature deviation and particle trajectories.

Different industrial tangentially fired boiler may have different tasks, and accordingly have different fuel input. Pulverized coal is now playing an important role in industrial boilers as its cheap fuel price and high heating values. The research on modeling pulverized coal combustion is also dominant in CFD application on boilers. [12-14] However, as fossil fuels are consumed dramatically around the world, substituting a part of a valuable fuel like Natural Gas (NG) or coal by a less valuable fuel such as Blast Furnace Gas (BFG) and Coke Oven Gas (COG) in the industrial boilers is an economical and environmental method [15], especially for a steel mill. Some literatures have report mixing fuel systems such as BFG/coal [16], BFG/NG [17] and BFG/COG [18,19]. In steel industry, the low calorific value residual gases generated both in ironmaking and steelmaking process, such as BFG, COG and Linz Donawitz Gas (LDG), are utilized as supplemental fuels by furnaces within the steel plant especially boilers to generate steam to provide mechanical energy, thermal energy and electrical energy [15,18,19].

The flow pattern and the combustion characteristics inside of the boilers are different under different fuel input. The BFG contains mainly nitrogen (N_2), with some carbon monoxide (CO) and carbon dioxide (CO_2), and little amount of hydrogen (H_2). The COG is composed mainly of hydrogen (H_2) and methane (CH_4). [15] Put low caloric value fuels into the tangentially fired boilers are frequently applied. Researchers are mainly focused on the efficiency and emissions when using these fuels.[20-23] However, the combustion characteristics with fuels (BFG and COG) supplement for CH_4 in the steel mill tangentially fired boilers are seldom reported. Through the motivation from a real industrial tangentially fired boiler in a steel mill facing steam tube failure problem, a detailed analysis of this type of boiler firing metallurgical gases is urgently needed and has a significant meaning.

Several CFD combustion models can be applied to simulate the combustion in the tangentially fire boiler. Based on different fuel input, combustion models for different boilers are varying from one to another. Mixture fraction probability density function (PDF) model was used for coal fired

boilers. [24-26] Kim et al [27] investigated the fuel lean reburning process in a 1.5 MW boiler which fired CH₄ as fuel. The computational combustion model they used was eddy dissipation (ED) model and the results validated with the experiment data including temperature and species. Parente et al [28] studied the effect of combustion models and kinetic mechanisms on the moderate or intense low-oxygen dilution (MILD) combustion. The results show that eddy dissipation/finite rate (ED/FR) model was unable to capture the volumetric features. While, Eddy Dissipation Concept (EDC) model with detailed chemistry provides more realistic results. Furthermore, Hjertager et al [29-30] presented various turbulent combustion models including the eddy-dissipation concept model. They report that the standard eddy dissipation concept model with multiple time scale turbulent mixer model can give good results. The Eddy-Dissipation Concept Model is an extension of the Eddy-Dissipation Model to finite rate chemistry, which assumes reactions occur on small scales and calculates a volume fraction of small scale eddies. It is also include detailed chemical mechanisms in turbulence flows. [31]

Sidewall overheating can lead to steam tube failure and operation shutdown. Broken tubes have to be replaced and thorough inspection has to be conducted in order to reset the boiler unit. According to the observation through cameras mounted inside the boiler, the overheating is believed to be the accumulated results of long-term, flame impingement. In this paper, a detailed numerical simulation of an industrial boiler firing metallurgical gases was conducted.

2 Methodology

In this CFD model, detailed turbulent combustion flow with heat and mass transfer was presented. The eddy dissipation concept turbulence combustion model was used to calculate the combustion reactions. The realizable k- ϵ turbulence model was applied to predict the flow turbulence. The P1 radiation model was used to take account of the dominant heat transfer flux.

2.1 General Transport Equations:

1 The Mass Conservation Equation (Continuity equation)

$$\nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

2 The Momentum Conservation Equation

$$\nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla_p + \nabla \cdot (\bar{\tau}) + \rho \bar{g} + \bar{F} \quad (2)$$

Where $\bar{\tau}$ is the stress tensor which is given by

$$\bar{\tau} = \mu \left[(\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \quad (3)$$

By the long-time averaged method, Equation (2) can be converted to Reynolds-averaged Navier-Stokes (RANS) equation as follows [32]:

$$\frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \sigma_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \frac{\partial}{\partial x_j} (-\rho \overline{u'_i u'_j}) \quad (4)$$

In Equation (4), the Reynolds stresses may be related to the velocity gradient by Boussinesq hypothesis as follows:

$$-\rho \overline{u'_i u'_j} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} (\rho k + \mu_t \frac{\partial u_k}{\partial x_k}) \sigma_{ij} \quad (5)$$

3 The Energy Equation

$$\nabla \cdot [\vec{v}(\rho E + P)] = \nabla \cdot [k_{eff} \nabla T - \sum_j h_j \vec{J}_j + (\bar{\tau}_{eff} \cdot \vec{v})] + S_h \quad (6)$$

Where E is defined as:

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \quad (7)$$

Where sensible enthalpy h is defined for ideal gases as

$$h = \sum_j Y_j h_j \quad (8)$$

where h_j is defined as

$$h_j = \int_{298.15K}^T C_{p,j} dT \quad (9)$$

4 Turbulence Model

The gas flow pattern in the **tangentially fired boiler** after entering the burner shows high turbulence intensity characteristic as its vortex mixing mechanism. This turbulence phenomenon can be solved by time averaged velocity scalar. The averaged Reynolds stresses term can be solved through the conservation of kinetic energy and dissipation rate, which called the k-ε turbulence model [33]. The Realizable k-ε turbulence model is used due to its ability to model flow with strong streamline curvature, vortices and rotation. It is a semi-empirical model based on the transport equation for the turbulence energy (k) expressed below respectively:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_K \quad (10)$$

$$\mu_t = c_\mu \rho \frac{k^2}{\varepsilon} \quad (11)$$

The generation of kinetic energy and buoyance force attribution are:

$$G_k = -\rho \overline{u'_i u'_j} \frac{\partial u_j}{\partial x_i} \quad (12)$$

$$G_b = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (13)$$

The turbulent dissipation rate (ε)

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b + S_\varepsilon \quad (14)$$

Where the equations are given on x_j direction. $C_1 = \max(0.43, \frac{\eta}{\eta+5})$, $\eta = S \frac{k}{\varepsilon}$, $S = \sqrt{2 S_{ij} S_{ij}}$, $S_{ij} =$

$\frac{1}{2} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right)$, C_2 and $C_{1\varepsilon}$ are constant.

5 Species Conservation Equation

During the operation process, the **natural** gas burns with the combustion air supplied from the burner, and the water evaporation happen in the high temperature circumstance. Therefore, species transport model can define the species and also calculate the species conservation and transportation. The local mass fraction of each species Y_i can be solved by the convection-diffusion equations. The conservation equation of each species can be expressed by

$$\nabla * (\rho \bar{v} Y_i) = -\nabla * \vec{J}_i + R_i \quad (15)$$

$$\vec{J}_i = -(\rho D_{i,m} + \frac{\mu_t}{Sc_t}) \nabla Y_i - D_{T,i} \frac{\nabla T}{T} \quad (16)$$

6 Combustion Model (Eddy Dissipation Concept)

The detailed Arrhenius chemical reaction kinetics of **natural** gas combustion can be incorporated in turbulent flames through eddy-dissipation concept model [34]. EDC model relies on the Kolmogorov cascade of energy dissipation on all lengths scales in turbulence flow. The chemical reactions and molecular mixing were assumed associate with turbulence dissipation occurred in fine structure of the flow. The source terms in the conservation equation for the mean species, i modeled as

$$R_i = \frac{\rho (\xi^*)^2}{\tau^* [1 - (\xi^*)^3]} (Y_i^* - Y_i) \quad (17)$$

$$Y_i = (\xi^*)^3 Y_i^* + (1 - (\xi^*)^3) Y_i^0 \quad (18)$$

$$\xi^* = C_\xi \left(\frac{v_\xi}{k^2} \right)^{1/4} \quad (19)$$

The reactions are assumed to occur in the fine structures over a residence time scale τ^* .

$$\tau^* = C_\tau \left(\frac{v}{\varepsilon} \right)^{1/2} \quad (20)$$

7 P1 Radiation Model

In the tangentially fired boiler, another heat transfer form is radiation due to the combustion occurred inside with high temperature around 2000K. Therefore, thermal radiation should be considered. Both discrete ordinate method and P1 model have been applied by previous researchers [35-36]. Ferreira [36] investigated two different numerical radiation methods to simulate a boiler and proposed that both the P1 approximation and Discrete Transfer Model are adequate for the radiation inside the boiler. The radiative heat flux as function of incident radiation intensity in P1 model is:

$$q_r = - \frac{1}{3(a + \sigma_s) - c\sigma_s} \nabla G \quad (21)$$

The transportation equation for incident radiation G is:

$$\nabla(\Gamma \nabla G) - aG + 4an^2 \sigma T^4 = S_G \quad (22)$$

$$-\nabla q_r = aG - 4an^2 \sigma T^4 \quad (23)$$

The expression for $-\nabla q_r$ can be directly substitute into the energy equation to account for the heat sources due to the radiation.

2.2 Simulation Code and Solution Method

This simulation was conducted by the commercial software package ANSYS Fluent 13.0. The Finite Volume Method (FVM) was used to solve the partial differential equations by discretized the equations using an upwind differencing scheme over the finite volumes. The SIMPLE algorithm was used to adjust the pressure and velocities after each iteration when solve the gas continuity and momentum equations. The calculations were conducted on the High Performance Computer (HPC) Peregrine1 (56 Gbps Infiniband interconnects, 8.4 TeraFLOPS) with 80 processors at Purdue University Calumet.

3 Geometry and Conditions

3.1 Computational Domain

Geometric model has been developed based on the drawings of boiler structure, which is shown in Figure 1. Steam tubes are distributed on the sidewalls and water running through the tubes are heated or vaporized for electricity generation and various purposes. In this simulation, the steam tubes are simplified as solid adiabatic walls and the wall temperature will represents the steam tube temperature. Three different fuel streams are feed to the four corners from the burners which shown in Figure 2. The cross section in the combustion zone is shown in Figure 3. Fuels come in from the burner ports, and then create a counter-clockwise thermo-flow pattern of recirculation. The fuels ports are Blast Furnace Gas (BFG), Coke Oven Gas (COG) and Natural Gas (NG). COG and NG inlets are partially surrounded by air inlets, producing a diffusion-like flame. “Hopper”, the bottom geometry, has slops of 15 degree tilted angle from the horizontal surface and a small opening.

3.2 Simulation Conditions

The solution to a flow problem coupled with heat transfer and chemical reactions by using the Finite Volume Method (FVM) is obtained at the nodes inside of each cell or grid. The accuracy of a CFD results is governed by the amount of cells. [37] In addition, grid refinement can reduce the false diffusion effect in numerical simulation especially in simulating a tangentially fired boiler. In this paper, in order to achieve accurate simulation results, mesh sensitivity study was conducted between a 5 million cells grid and a 6 million cells grid, which shows no difference. Therefore, the 5 million cells grid was used to conduct the following simulation as to save some computational time. This simulation is based on the real operation conditions of a certain tangentially fired boiler. The boundary conditions and fuel properties are taken directly from the operation database.

Based on the composition of the fuels, the chemical mechanisms are referred from the ANSYS Fluent database which is shown in Table1. The fuel properties are shown in Table2.

4 Results and discussions

4.1 Validation

In order to validate CFD model, field experiments were conducted. Under different operation conditions, distinctive flow characteristics and flame profiles were captured by video camera. Therefore, the developed CFD model applied these two different operation conditions and compared the results with field experiments. The boundary conditions of these two different situations were listed in Table 3. The turbulence boundary conditions were defined based on the inlets intensity and hydraulic diameters. The two different cases have different fuel composition and total energy input.

Field experimental videos of the two different cases are shown in Figure 4. The flow characteristics and flame profiles are distinctively different. Simulation works based on the developed CFD model of these two cases are also conducted. The results are post-processed by using software Tecplot and ParaView to visualize the flow characteristics and flame profiles. Temperature contours and streamlines were also post-processed as shown in Figure 5. Temperature contours at the center level of the combustion zone are shown in Figure 6. CO species iso-surface when the mass fraction equals to 0.01 is showing in Figure 7, which could represent the flame shape.

According to Figure 4, the top view of combustion zone indicates that the difference of the flow characteristics and flame profiles are distinctive under two different operating boundary conditions. For high total fuel input Case1, the flames originated from four corners connect with each other and form a strong circulation in the boiler. However, for the lower total fuel input Case2, the flames are sticking to the walls. Comparing to the Case1, the flame vertex actual tangential circle diameter of Case2 is bigger, which means the circulation formed in the center is less strong than Case 1.

The actual tangential circle diameter is a very important parameter to evaluate the flow properties inside of a tangentially fired boiler. And which can be calculated in the following equation:

$$d = \frac{\frac{d_1}{A} + \frac{d_2}{B}}{2} \quad (24)$$

Figure 5 shows the flow streamlines of these two different situations got from the developed CFD model. The streamlines are colored by temperature. It can be seen from the streamlines that the

circulation strength and flow directions are different. For Case1, the strong flow circulation was formed at the center of the boiler where the high temperature flames were also stay away from the wall. However, for Case2, the high temperature streamlines are directed to the walls. These two different situations are agreed well with the video captures in Figure 4. The actual tangential circle diameters can be read from Figure 8 according to peer's research [4]. The actual tangential circle diameter of Case1 is smaller than Case2 with high peak tangential velocities are closer to the center on x and z directions shown in Figure 8.

The temperature contours in Figure 6 indicate the flame positions at the center level of the combustion zone. For Case1 with higher input momentum, the high temperature flames are around the cold fuel streams shown in Figure 6. Some of the high temperature flames are directed to the burner, which match with the field video. For Case2 with lower input momentum, the high temperature combustion flames are moving towards the walls. The flame profiles are represented by the species CO concentration. [38-39] Species CO mass fraction 0.01 was used to represent the flame outlines. The difference of the flame profiles under these two different operation conditions can be read in Figure 4. Results for the CFD model are post-processed in Figure 7 which agrees with the field video captures. Therefore, the developed CFD model is validated by comparing the simulation results with field experimental video under different operation conditions.

4.2 Overheating Phenomena

4.2.1 Overheating Position

By using the validated CFD model, the impact of flames on the steam tubes which simplified as adiabatic walls has been simulated. This simplification would lead to the temperature on the wall higher than the real situation, but can predict trend of the overheating problem. The temperature contours at the front wall and left wall are shown in Figure 9.

Figure 9 shows the temperature contours at the front and left side walls, which indicate a steam tube overheating phenomena in this tangentially fired boiler. There are two major hot spots on each side of the wall, one is near the burner in the combustion zone and the other is above the combustion zone. The hot spots are approximately 100K higher than other places. Long time hot spots affect the steam tubes and this temperature deviation would cause the tube failure accidents

in the real operation. Based on previous research work and industrial feedback, under different operation conditions, the steam tube failure places are similar and agree with the CFD results.

4.2.2 Hot Spot Definition

A group of typical operation conditions with power output ranges from 100 MW to 200 MW were evaluated by using the validated CFD model. These typical operation conditions are listed in Table 4. Eleven operation conditions were selected which shown different hot spots temperatures. The first five cases have higher wall average temperature and peak temperature than the other six cases, which shown in Figure 10.

According to Figure 10, the maximum difference between Case2 and Case10 on the average wall temperature is around 100K. And the average wall temperature of the first five cases is higher than the other cases. Compare to the average temperature on the wall, the peak temperature would have more effect on the steam tube overheating problems. The long time temperature deviation on the steam tube with high hot spot peak temperature impingement increases the risk of steam tube failure greatly. It can be seen that the maximum difference of peak temperature among all the operation cases is approximately 150K. All the cases are under the typical operation conditions which covered most of the situations. As some of the typical operation conditions do not lead to serious steam tube failure problem, which would be considered as safe situation. While some other cases did cause overheating problems. Therefore, the temperature between 750K and 900K on the steam tubes would be harmful to the steam tubes life, which is defined as a hot spot in this simulation.

4.2.3 Hot Spot Area

Based on the definition of the hot spot on the steam tube, the area of the hot spot was clipped by setting up the temperature range from 750K to 900K. The hot spot area also has a great effect on the steam tubes. Long time exposed with hot spot, the steam tube would suffer the imbalance of stress forces and lead to the steam tube failure problems. The hot spot areas under different operation conditions are shown in Figure 11.

According to Figure 11, the hot spot area under different operation conditions appears different. The first five cases have larger hot spot area than the other cases. The differences of hot spot area appear dramatically big between the Case2 and Case 10, which represent for the risk and safe operation conditions, respectively.

Therefore, in terms of steam tube overheating problem, there are two criteria to judge the extent of impact on the steam tubes, one is the peak temperature and the other is area of the hot spots. When reducing the hot spots peak temperature to a certain degree which the steam tube steel can stand, the risk of steam tube failure problems will be reduced. If the hot spots area can be further reduced, the risk of steam tube failure will be further reduced. This hot spot area and peak temperature will be used as judgments on safe and risk operation conditions.

4.3 Parametric studies

In order to optimize the operation of the tangentially fired boiler firing metallurgical gases to get rid of steam tube failure problems, a further study on optimizing operation parameters was conducted. Based on previous study on a great amount of cases under different operation conditions, the effects of total fuel input and the NG percentage were investigated.

4.3.1 Effect of Total Fuel Input

Tangentially fired boilers in steel mills are always under different fuel input loads at different time according to their demands. Under different fuel loads, the combustion processes and flow characteristics are shown different according to the validation cases. And the impact on the steam tube overheating problems would be different. Therefore, a study on the effect of different fuel input loads on the steam tube overheating is necessary.

Based on the real operation conditions of the tangentially fired boiler in one steel mill, three different fuel input loads are applied to investigate the effects on the flow characteristics and overheating problems. The boundary conditions are shown in Table 5.

The total fuel input loads has great effect on the combustion process and side wall temperature distributions. The temperature contours at the **natural** gas inlet level for three different fuel input

load cases are shown in Figure 12. The side walls peak temperature and hot spots area are plotted in Figure 13 (a) and (b).

It can be seen from Figure 12 that different fuel input loads have great effect on the flow characteristics and temperature field. The temperature contour of the low load fuel input shows that the fuel input under this condition could not help to form a tangentially circulated flame in the center. Meanwhile, the high temperature flames are directed to the wall near the burner, which would cause some overheating problems. After further increasing the fuel input load, the input fuels can form a strong circulated circle in the center of the boiler and combustion mainly occurred around the circle. The formed tangential circle can help to improve the combustion process and also avoid the flame impingement phenomenon. When further increase the fuel input load, the tangential flow circle show similar pattern with higher combustion temperature in the circle and center.

According to Figure 13, with the increasing of fuel input load, the peak temperature at the side wall firstly decreases and then increases. However, the side wall peak temperature at the low load fuel input condition even higher than the high load fuel input condition, which is due to the flame impingement under low load fuel input when a tangential combustion circle can not be formed. Meanwhile, when the fuel and air streams form a tangential circle, the further increasing of fuel input will lead to increasing of side wall peak temperature. In addition, with the increase of fuel input load, the hot spot area on the side walls is also first decrease and then increase, which shows similar trend with side wall peak temperature. Under this criterion, the case with medium fuel input but can form a strong circulation in the boiler is benefit for the boiler operations and can help to reduce its risk of steam tube failure problems.

4.3.2 Effect of NG Percentage

For this particular boiler mainly firing metallurgical gases, the NG input percentage has a great effect on the side wall temperature in the combustion zone. According to its operation conditions, exceed of 10% NG input would not applicable during the field operation. Therefore the effect of NG input percentage from 0% to 10% was conducted under the high fuel input load condition.

Based on the validated CFD model, the simulation was conducted under the six different operation conditions. The effect of NG input percentage on the side wall temperatures and hot spot areas in the combustion zone has been analyzed based on the results. The results are plotted in Figure 14. With the increase of NG percentage, the average temperature on two side walls and the peak temperature in the hot spots are firstly decreased and then increased. 2% of NG input case has lowest peak temperature among other cases. The hot spot temperature has a difference about 100K between 2 percent input and 10 percent NG input boundary conditions. For the hot spot area, from 0 percent to 10 percent NG input, it decreased from 1.7763 m^2 to 1.1571 m^2 and then increased to 13.4787 m^2 rapidly. Therefore, a suggest NG input percentage at the high load operation conditions should be around 2%.

5 Conclusions

A detailed three-dimensional computational fluid dynamics model for an industrial tangentially fired boiler firing metallurgical gases was developed. Eddy dissipation concept turbulence combustion model was used to solve the turbulence flow with combustion. The model was validated by comparing the model predicted flame profiles to the real operation video capture under different operation conditions. The simulation results showed hot spots on the furnace wall. The hot spot temperature and area are determined based on investigating a wide range of operating conditions. The parametric study results suggested that total fuel input has great effect on the steam tube overheating problems. Proper total fuel input would help to form a strong circulation in the tangentially fired boiler to avoid flame impingement on the steam tube. Natural gas input has significant effect on the wall temperature, and 2 percent (volume) is the optimal value for operation to avoid overheating problem.

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7 Nomenclatures

A	Width of the tangentially fired boiler at a certain cross-section area
B	Length of the tangentially fired boiler at a certain cross-section area
C	Linear-anisotropic phase function coefficient
p	Static pressure, pascal
ρ	Density, kg/m ³
$\bar{F}$	External body force, N
S_m	Mass added to the continuous phase from the dispersed second phase (e.g., due to vaporization of liquid droplets) and any user-defined sources
$\bar{g}$	Gravity, m/s ²
$\bar{\tau}$	Stress tensor
μ	Molecular viscosity, kg·m/s
I	Unit tensor
k_{eff}	Effective conductivity, w/m-K
h_j	Sensible enthalpy of species j
$\vec{J}_j$	Diffusion flux of species j
S_h	Heat of chemical reaction, and any other volumetric heat sources, J
k	Turbulence energy, m ² /s ²
σ_{ij}	Stress tensor due to molecular viscosity
ϵ	Turbulent dissipation rate m ² /s ³
σ_k	Turbulent Prandtl number for k , 1.0
σ_ϵ	Turbulent Prandtl number for ϵ , 1.2
μ_t	Turbulence viscosity, kgm/s
β	Thermal expansion coefficient K ⁻¹
$\vec{v}$	Velocity, m/s
u_j	Velocity component along the direction x_j , m/s
u'_i	instant turbulence velocity on the direction x_i , m/s

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G_k	Generation of turbulence kinetic energy due to the mean velocity gradients, m^2/s^2
c_μ	Constant
Pr_t	Turbulent Prandtl number for energy
g_i	Component of the gravitational vector in the i th direction, m/s^2
G_b	Generation of turbulence kinetic energy due to buoyancy, m^2/s^2
Y_M	Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
S	Modulus of the mean rate-of-strain tensor
S_K	User defined source term
S_ε	User defined source term
$C_{1\varepsilon}$	Constant, 1.44
C_2	Constant, 1.9
d_1	Intervals between maximum tangential velocities width directions
d_2	Intervals between maximum tangential velocities length directions
a	Absorption coefficient, m^{-1}
n	Refractive index
σ_s	Scattering coefficient, m^{-1}
σ	Stefan-Boltzmann constant ($5.67 \times 10^{-8} \frac{W}{m^2 K^4}$)
T	Local temperature, K
Y_i	Local mass fraction of each species
$C_{p,j}$	Constant pressure specific heat of species j
R_i	Net rate of production of species i by chemical reactions
$\vec{J}_i$	Diffusion flux term of species i
$D_{i,m}$	Diffusion coefficient for specie i in the mixture
$D_{T,i}$	Thermal diffusion coefficient
Sc_t	Turbulent Schmidt number, 0.7
Y_i^*	Mass fraction of species i within the fine structures after reacting over the time τ^*
Y_i^0	Mass fraction of species i in the fluid surrounding the fine structures
ξ^*	Mass fraction occupied by the fine structure regions
C_ξ	Volume fraction constant, 2.1377

ν Kinematic viscosity m^2/s

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Table 1 Reaction Mechanisms

Fuel	Global chemical reaction
Methane	$1\text{CH}_4 + \frac{3}{2}\text{O}_2 \rightarrow 1\text{CO} + 2\text{H}_2\text{O}$
	$1\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow 1\text{CO}_2 + 0\text{H}_2\text{O}$
Hydrogen	$1\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow 1\text{H}_2\text{O}$
Ethane	$1\text{C}_2\text{H}_6 + \frac{7}{2}\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O}$
Ethylene	$1\text{C}_2\text{H}_4 + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O}$

Table 2 Fuel Species Compositions

Species	BFG	COG	NG
O ₂		0.004	
N ₂	0.47	0.04	
C ₂ H ₆		0.008	0.029
C ₂ H ₄		0.022	
CH ₄		0.253	0.944
CO ₂	0.25	0.026	0.027
CO	0.22	0.05	
H ₂	0.06	0.597	
H ₂ O			

Table 3 Boundary conditions

Cases	Case1 (m/s)	Case2 (m/s)	Temperature (K)
Air inlet	25.6	21.96	349.80
Coke Oven Gas inlet	16.55	19.39	298.70
Blast Furnace Gas inlet	3.92	7.28	310.93
Natural Gas inlet	173.48	46.59	295.37

Table 4 Boundary conditions of the typical operation conditions

Cases	BFG (m/s)	COG (m/s)	NG (m/s)	Air (m/s)
1	8.37	14.33	155.66	23.89
2	12.55	0	202.58	20.07
3	4.28	7.34	79.49	20.07
4	10.46	17.92	194.56	23.89
5	8.01	0	129.02	23.89
6	17.71	15.53	115.22	22.55
7	13.5	12.6	84.9	19.1
8	14.5	0	42.775	20.07
9	11.6	0	34.22	20.07
10	16.63	25.87	55.84	20.07
11	13.31	20.69	44.71	20.07

Table 5 Different input fuel load boundary conditions

Cases	BFG (m/s)	COG (m/s)	NG (m/s)	Total Input	Fuel
1	9.05	7.95	58.64	Low Load	
2	13.50	12.60	84.90	Medium load	
3	17.71	15.53	115.22	High Load	

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