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Steady State model of a Reheating Furnace for determining slab boundary conditions

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Abstract

The slab reheating process in a reheating furnace is a very energy intensive process with many operating parameters that can be optimized. Numerical methods are therefore applied to generate models which can be used in an optimization strategy. This paper presents the first step in the creation of these models: obtaining the boundary conditions for the slab model from a steady state model of the furnace. The slab heating process itself is a transient phenomenon and an accurate cross-sectional slab temperature cannot be obtained using a steady state model. The furnace however, operates in a narrow range of temperatures and steady state operation is a suitable approximation. The steady state model is calibrated with data from a working reheating furnace at the ArcelorMittal Gent site. The numerical results show a good agreement with the experimental data with an average relative error of 3.1%. This gives confidence in using this model to determine the furnace heating boundary conditions of the slab model which will be implemented in future work.

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1. Introduction

ArcelorMittal is one of the largest steel producers in the world and the Gent plant is one of the largest within ArcelorMittal. The reheating process alone requires massive amounts of energy every year (about 7 PJ). This energy mainly comes from the in-house produced coke oven gas and imported natural gas. The process of hot rolling of steel starts with the heating of slabs in a reheating furnace. The heat transfer inside the furnace is accomplished primarily with the help of radiation from the burning gases and furnace walls. When a slab is first charged into the

furnace, it is stationed in the pre-heating zone where the hot combustion gases heat it up to about 900°C. Once it enters the heating zone, the primary mode of heat transfer is radiation and here the slab is heated to a desired temperature. However at this point, the slab is still colder in the middle than the surface while uniform temperature throughout the slab is very important for the consequent rolling process. Therefore, in order to obtain uniform cross-sectional slab temperature, it needs to be stationed in the furnace for longer periods of time. This results in an increased energy use and consequently an increase in CO₂ emissions. Energy efficient heating patterns are therefore established to obtain uniform temperature throughout the slab. The use of numerical models is beneficial in this regard, as a fast and accurate numerical model allows for efficiently evaluating the slab heating scenarios.

The process of reheating of slabs inside the reheating furnace is complex and involves heat transfer between combusting gases and various surfaces inside the furnace [4]. The main mode of heat transfer is radiation [1] (more than 90%) from the combusting gases and the furnace walls in the heating and soaking zones, with convection as the dominant mode of heat transfer in the pre-heating zone. Studies have been conducted to model the heat transfer into the slab using numerical methods [1]. However, the complexity in the heating process increases the computational cost to the point that they are not usable in actual applications, thus necessitating significant model simplifications. We develop a steady state model of the entire furnace so we can obtain the heat fluxes to the slabs. The model will be validated using the thermocouple measurements inside the furnace which will give us the operating temperature range of the furnace.

This work presents the first step in the development of a computationally complex, yet efficient model, in order to simulate the heat transfer into slabs in a walking beam reheating furnace. It follows a similar approach as that of Preiler et al. [3] for combustion modelling in steady state conditions. The furnace under consideration has 60 burners distributed inside the furnace in three major zones and uses coke oven gas (COG) as primary fuel. A few simplifications have been adopted in the model like neglecting the skid-slab contact heat transfer and scale formation as they influence the slab heat transfer and not the overall temperature distribution of the furnace.

2. CFD model and methodology

The CFD model in this work incorporates turbulent combustion flows with heat and mass transfer using the commercial code of Ansys Fluent[3]. Chemical equilibrium state relations are used in the non-premixed combustion model and the Realizable k-epsilon turbulence model is used to account for the flow turbulence. The radiation is modelled using the Discrete Ordinate (DO) radiation model.

2.1 Computational Domain

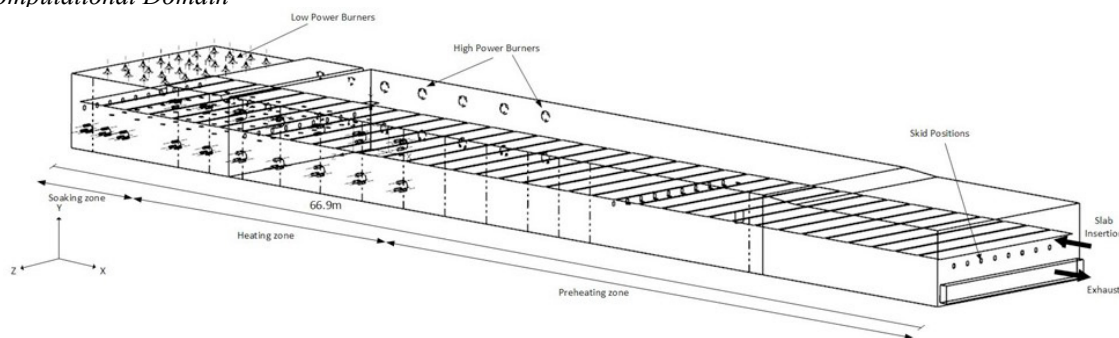


Fig. 1. Computational Domain

The geometry of the computational domain, see Fig. 1, was developed based on the furnace in commission at ArcelorMittal Gent. It is subdivided into three major zones: the pre-heating zone, the heating zone and the soaking zone. The slabs are charged from the charging door and move through the furnace with the help of walking beams before being dropped out through the discharging door. Burners of different capacity are installed throughout the furnace. High power burners are installed on the walls in the heating zone and several low powered burners on the roof of the soaking zone. All these burners have a combined maximum capacity of approximately 137MW.

2.2 Boundary Conditions

The fuel composition and the burner volume flow rates are constantly changing with time. The thermocouple measurements inside the furnace were observed for 6 hours and every second measurements were taken at different points on the roof of the furnace along with burner flow rates and gas compositions. It was found that the temperatures were constantly fluctuating with the change in fuel composition and burner flow rates. So in order to validate our numerical results we found a range of temperatures within which the furnace operates. The validation curve in Fig. 5 shows the maximum and minimum temperatures within which the furnace operates. Based on this data from the furnace, a set of operating conditions for each burner have also been defined consisting of fuel composition and gas flow rate. The furnace wall emissivity was taken as 0.75 [1]. Variable thermal properties (emissivity, specific heat and thermal conductivity) of the steel slabs were obtained from ArcelorMittal and incorporated in the model. In this study, the slabs are considered to be stationary, so we prescribe a constant slab temperature that corresponds to the temperature of the slab as it moves through the different zones in the furnace. So for example the temperature of slab 18 is taken as 725 °C and this temperature corresponds to the experimentally determined temperature of a slab as it reaches the position of slab 18 inside the furnace.

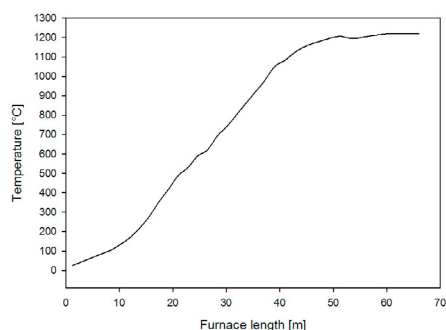


Fig. 2. Assumed slab temperatures

The effect of the cooling skids on the slab heat transfer is neglected in this steady state model but in order to take into account the heat loss due to the skids we have assigned a constant wall temperature to the skid surfaces. In order to account for other losses like furnace door opening in the charging and discharging ends, heat loss from the walls of the furnace and heat loss from gaps inside the furnace we have considered an additional loss of 20% [2]. The numerical grid for the furnace model consisted of 39,908,423 elements and was refined to 49,390,134 & 63,899,725 elements. The temperature profiles obtained from the refined meshes had negligible deviations from the thermocouple measurements, hence the mesh with 39,908,423 elements was chosen for further calculations.

2.3 Material Properties

The gas used as fuel for the combustion is a mix containing primarily COG (Coke Oven Gas) and Table 1 gives the composition of fuel and air used in this study.

Gas Species	Fuel (mass%)	Oxidiser (mass %)
Nitrogen (N ₂)	14.19%	79%
Oxygen (O ₂)	0%	21%
Methane (CH ₄)	39.96%	
Hydrogen (H ₂)	25.16%	
Ethane (C ₂ H ₆)	1.87%	
Ethylene (C ₂ H ₄)	1.87%	
Carbon dioxide (CO ₂)	7.01%	
Carbon monoxide (CO)	9.90%	

Table 1. Composition of fuel and air.

The material properties of the furnace walls we obtained from the data sheets given by ArcelorMittal.

3. Results and Discussions

3.1 Furnace Characteristics

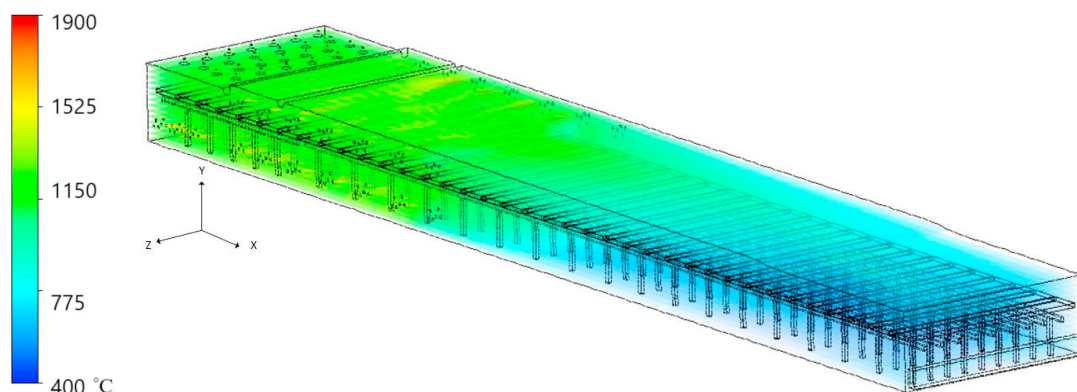


Fig. 3. Furnace Temperature distribution

Fig. 3 shows the volume rendering of the temperature distribution in the furnace. The high temperature streams show the combustion gasses that are introduced into the furnace. The pre-heating zone of the furnace is in a range of 600-800 °C which is due to the cooling of the gases towards the end of the furnace. The heating zone is maintained at a temperature of 1200-1300 °C and the high powered burners stationed in this zone are responsible for heating the slab up to the required temperature. The temperature in the soaking zone is reduced to 1100-1200 °C with the main purpose of obtaining temperature uniformity inside the slab. Fig. 4 shows the velocity streamline originating from the burners which show the path and velocity distribution of the combusting gases inside the furnace. It shows maximum velocities at the burners and as the gases reach the exhaust of the furnace we see a rise in velocity again.

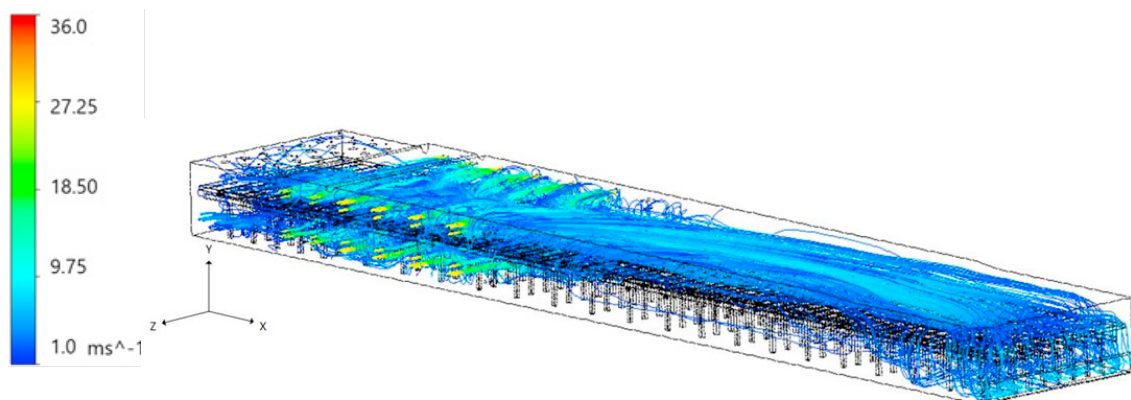


Fig. 4. Furnace Velocity distribution

Fig. 5 shows the comparison of the predicted temperature using the CFD model with those measured by the thermocouples inside the furnace. The temperature plot obtained from the model was found to be in good agreement with the measured temperatures. A minimum deviation of 2 °C was found in the heating zone and a maximum deviation of 89 °C was found in the beginning of the heating zone.

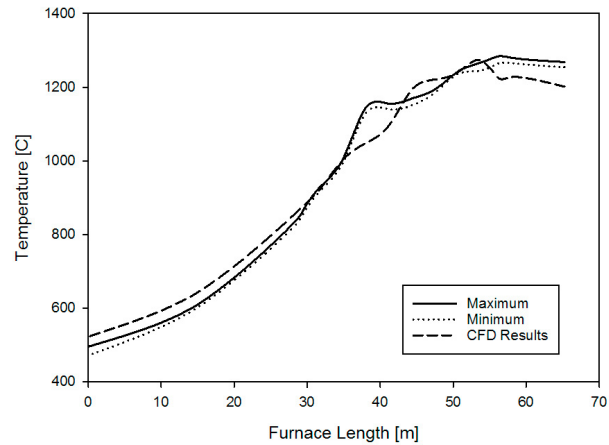


Fig. 5. Comparison of model prediction with thermocouple measurements

3.2 Slab Characteristics

The centre-line heat flux distribution on the top and bottom of the slab surfaces can be seen in the plots of Fig. 6(a) and Fig. 6(b). On average, more than 90% of the total heat flux is radiation. Only in the beginning of the pre-heating zone we see an increase in the convective flux. It can also be seen that on average the top surface of the slab receives much higher fluxes compared to the bottom surface which is due to the accumulation of the hot gases on the roof of the furnace as shown in the velocity streamline plot of Fig. 4. As we move further down the pre-heating zone towards the heating zone we notice the peaks in the radiative heat flux which is due to the difference in temperature between the cold incoming slab and the high temperature combustion gases. As the slab moves further its temperature starts to increase and the heat flux starts dropping rapidly.

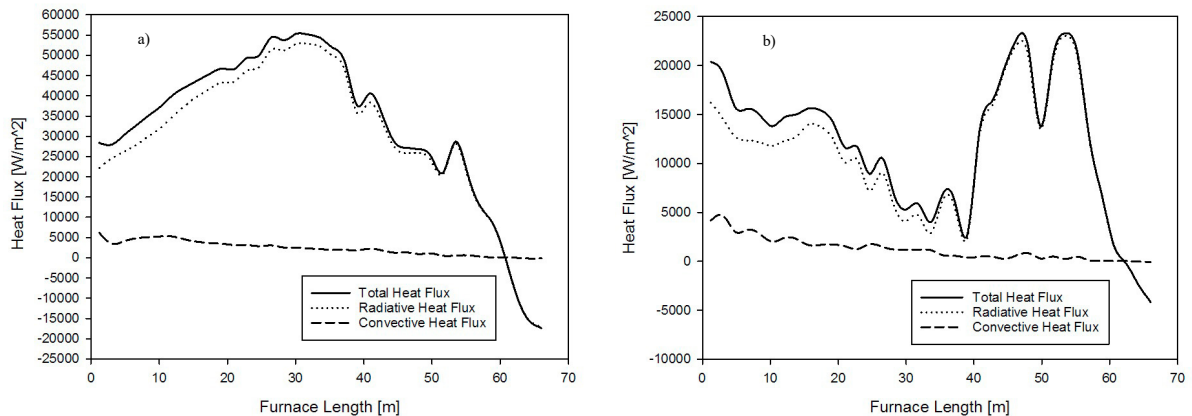


Fig. 6. Heat flux[kW/m²] on the slab surface (a)Top surface (b)Bottom surface

In the region between the end of the heating zone and beginning of the soaking zone (around 50 meters) there is a dip in the heat flux due to the separation of the flow streams in the beginning of the soaking zone. The flow stream at this point has a stream going towards the exhaust of the furnace and another stream going towards the soaking zone. So the fluxes at this point drops a bit due to the absence of hot gases and rises again in the soaking zone. It finally drops to negative values towards the end of the furnace as slab temperatures are hotter than that of the

medium. The heat flux plot in Fig. 7 shows the surface plot of the variation of the radiative heat flux on the top surface of the slab along its length as well as along the length of the furnace.

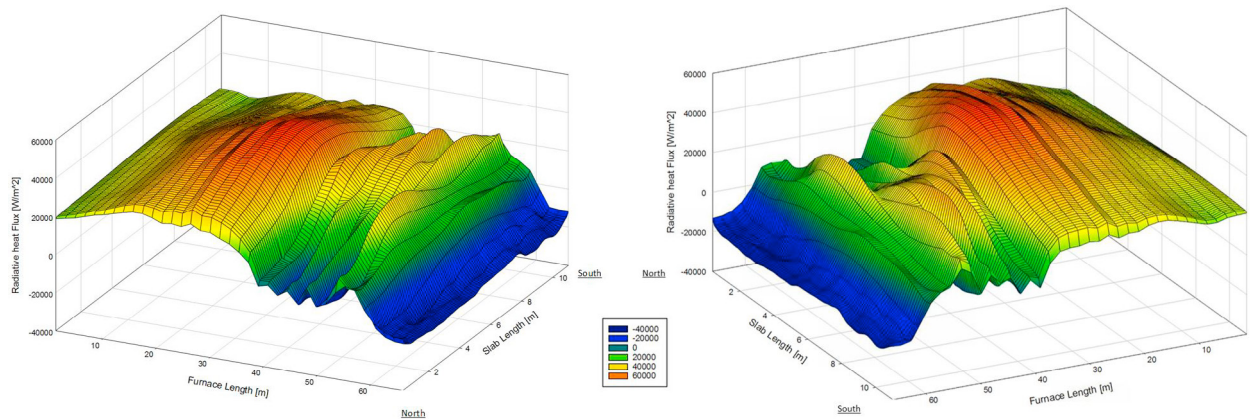


Fig. 7. Radiative heat flux [W/m^2] on the slab top surface along furnace length

4. Conclusion

In this work a steady state model has been presented in order to obtain the radiative and convective heat fluxes which can be used for developing a computationally less expensive model. The temperatures obtained from the CFD model were compared with the thermocouple measurements inside the furnace and found to be in good agreement. The plots for the heat flux on the surface of the slabs show that the maximum heat flux on the slab is towards the end of the pre-heating zone where there is a maximum difference in temperature between the medium and the slab. They also reveal that the radiative heat flux dominates the heat transfer with an average of 93% of the total heat flux in the soaking zone, heating zone and downstream in the pre-heating zone. Only in the beginning of the pre-heating zone we observe higher values of convective heat flux which amounts to an average of 13% in that zone.

5. References

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