NUMERICAL INVESTIGATION ON THE INFLUENCE OF THE SKID COOLANT TEMPERATURE ON THE REHEATING FURNACE PERFORMANCE

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Abstract

Steel making is one of the most energy intensive production process employed today. It involves different types of furnaces depending on the stage of the steel production process. Each of these furnaces operate at different temperatures that are used in the melting, reheating or annealing of the crude steel that is produced. This paper concerns the reheating process, where steel slabs are reheated for the subsequent hot rolling process. In this work a reheat furnace is studied using computational fluid dynamics with the objective of understanding the sensitivity of the skid coolant temperature on the performance of the reheat furnace. These skids transport the charge (slabs or billets) throughout the length of the furnace. Since these skids run through the entire length of the furnace, the influence of these is significant both for the furnace performance and product quality. The coolant temperature in these skids is varied and its influence on the furnace and charge quality is assessed. This is achieved by analysing the furnace temperatures and the heat fluxes both on the slab and at the skid slab contact points. This approach is experimentally validated and in this work, it is used to show the influence of skid coolant temperature on the temperature distribution inside the furnace and on the severity of the skid marks that arise due to the skid slab contact.

Keywords: CFD, steel, reheat furnace, truncated model

Introduction

Steel is one of the most important materials: it is widely used in construction, production and transportation. Its importance lies in its strength, durability and recyclability. However, steel production is a highly energy-intensive process and is one of the major contributors CO_2 emissions and its related effects of global warming. It is however extremely difficult to replace steel with any other material and there lies the importance of low carbon steel production methods. The steel industry has been trying to lower its carbon footprint using various technologies like Direct Reduced Iron (DRI) furnaces and recycled steel. These technologies, although being very effective, require large investments to commission them, which is not easily applicable to most manufacturers. Energy efficiency therefore is key in lowering the emission levels of the existing steel plants without major changes to their processes.

The subject of this paper is the reheat furnace for the hot rolling process, which is a crucial component of the steel manufacturing process. It is an intermediate step between the caster and the cold rolling process. It is designed to reheat steel billets/slabs, making them suitable for hot rolling operations. The charge (slabs in this case) is heated to about 1200 °C, which improves the material's plasticity along with elimination of any residual stresses, improving its mechanical properties. Reheat furnaces, like most high temperature furnaces, are steel enclosures lined with refractory material. The thickness of the lining varies within the furnace but always consists of multiple layers to ensure the highest possible heat insulation.

The temperature inside the furnace is regulated using advanced control systems that can modulate the flow and composition of the gaseous fuel that is combusted in order to obtain these high temperatures.

The furnace is divided into three zones: the pre-heating zone, the heating zone and the soaking zone. There are different types of burners installed inside the furnace depending on the temperature requirements of that zone. This zonal temperature is maintained in order to follow the temperature evolution of the slab as it is being heated through the different zones in the furnace. The zonal temperature also dictates the fuel blends that are used for these burners. In the pre-heating zone regenerative burners are used which are equipped with heat exchangers that pre-heat the low-heating value gaseous fuel. While, in the heating and soaking zones classical flameless burners are installed which operate on coke oven gas and uses air that is pre-heated using the exhaust stream. The charge itself is transported inside the furnace using skids that run throughout the length of the furnace. These skids are water-cooled in order to preserve their structural integrity. The cooled skids are constantly in contact with the charge and act has heat sinks for the hot slabs. This results in the formation of cold spots in the charge (slab). These cold spots are detrimental to the product quality as they can generate defects in the hot rolling process. Significant care is taken to avoid these cold spots (also known as skid marks) in the soaking zone of the furnace. Most furnaces try to reheat the cold spot by changing the position of the skids or by stationing the slab in the soaking zone for longer periods of time to ensure the dissolution of the cold spot.

The detrimental effect of skid marks is a well-known problem and using numerical modelling techniques to study skid marks has received a lot of attention in the past. Typically full-scale transient models have been used to model both the furnace behaviour and the slab reheating process. Han et al. [1] modelled the slab heating process and compared the heat fluxes for both top and bottom of the slabs for that particular furnace-skid system. The model also calculated the evolution of the skid mark temperatures throughout the reheating process. Ahmed et al. [2] did a similar study on the influence of the water-cooled skids on the slab reheating process. A steady-state approach was used to model the furnace and heat fluxes on the slab bottom surface. A case with and without skids were used to show the impact of the skids and the skid-slab contact on the heat fluxes. Morgado et al. [3] and Wang et al. [4] both included the skids in their full-scale furnace models but a detailed analysis of the skid marks were not the focus of their work. However, a detailed full-scale transient simulation of the furnace along with experimental investigation was carried out by Tang et al. [5]. A moving mesh approach was used to model the slab movement through the furnace and cross-sectional temperatures were resolved along with an analysis of the skid marks. These simulated temperatures were validated using slab trail experiments, where thermocouples were placed in strategic locations inside the slab in order to monitor the evolution of the slab temperatures during the reheating process. Xu et al. [6] used a similar approach to model the effects of the skid buttons and the effect of their dislocation on the reheating of the cold spots. Further details were added in the models of Pengju et al. [7] where the skids were modelled up to the different component layers to obtain extremely accurate heat fluxes on the slab contact. Ahmed et al. [8,9] proposed the truncated approach, which is a combination of a steady-state model with a smaller truncated transient slab model. Ahmed et al. [9,10] also proposed a means to objectify the influence of the skid marks on the cross-sectional temperatures. However, none of the aforementioned works offer possible solutions to solve or at least minimize the skid-mark problem.

In this paper a higher skid coolant temperature is proposed as a possible means to minimize the effect of cold spots. This idea is quantifiable in two aspects, i.e. on the furnace level and on the slab level. Keeping in mind the confines of a conference publication, only the influence on the furnace level is discussed here. The influence on the slab level is extremely important, however it merits at least the basic clarifications on the truncated approach and detailed discussions on the slab level simulation results. Therefore, in this paper both the furnace and the slab characteristics are discussed, but only from the perspective of the furnace. It is observed that increasing the coolant temperatures significantly impacts the temperature distribution in the bottom half of the furnace, hence it has an equally significant influence on the heat fluxes on the slab surface. These effects are quantified using temperature contours of the furnace and heat fluxes on the slab surface.

Methodology

The steady-state model of the furnace simulates the furnace in its entirety with all of the geometric details. In this section a detailed description of the model is provided along with the sub models and the material properties and relevant boundary conditions of the components. The simulations were carried out using ANSYS Fluent 2022 R2 [11,12].

Computational domain

A typical furnace is divided in to three primary zones: the pre-heating zone, heating zone and the soaking zone. The furnace under consideration has an additional recuperative zone, which houses regenerative burners. Figure 1 shows the computational domain as it is employed in the CFD calculations. The furnace is about 70 m in length, 11.4 m in width and about 4.5 m in height which varies depending on the zone. Furnace temperatures gradually increase from about 600°C in the pre-heating zone to a maximum of about 1350°C in the heating zone, before lowering to about 1200°C in the soaking zone. Burners of varying power are placed in the different zones to follow this designed slab temperature evolution. The walls of the furnaces are also defined as a refractory walls with varying thicknesses depending on the location inside the furnace.

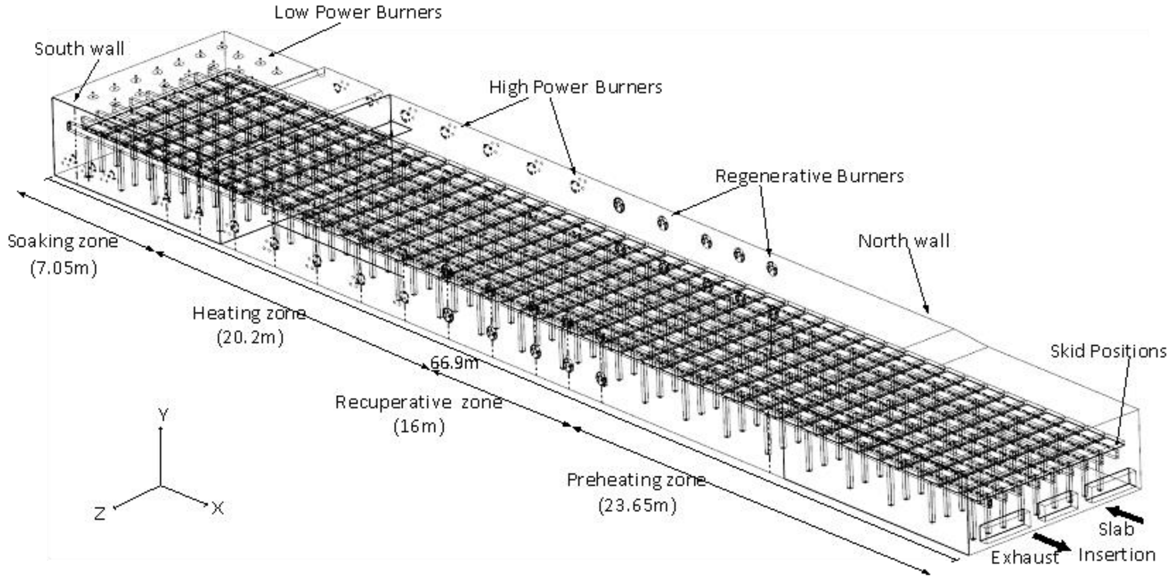

Figure 1 Computational domain of the furnace

The slabs rest on water-cooled skids which are also modelled in significant detail. Figure 2 shows the CAD drawings of the skid assembly inside the furnace. There are two types of skids: fixed (yellow) and moving (red). The moving skids transport the slabs through the furnace while the fixed skids support the skids while they rest in a particular zone. In the furnace there are three sets of these skids. These skids change position in the soaking zone much like the furnace modelled by Xu et al. [6].

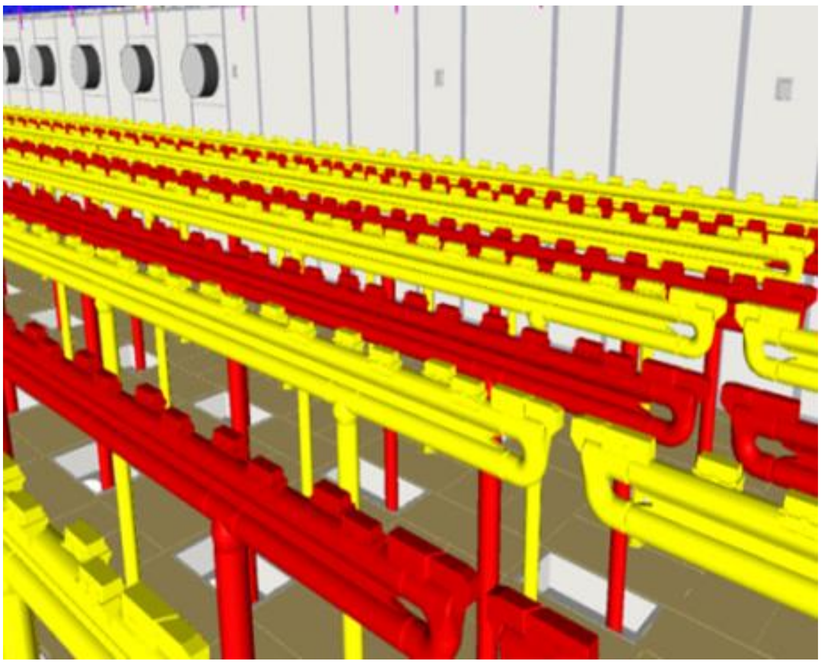

Figure 2 Detailed drawing of the skid system in the reheat furnace

A detailed schematic of the different components of the skid is shown in figure 3. The skids are covered with refractory shielding and the rider blocks are directly in contact with the steel pipes. In the CFD model a simplification is made in order to avoid complicated meshing scenarios. The rider blocks are not placed in contact with the pipes but rather sit on top of the skids. Appropriate boundary conditions like pipe inner wall temperature (200 °C), rider top surface temperature (slab temperature) and rider bottom surface temperature (200 °C), etc. are applied to the entire skid system. The outer surfaces of the skids are assigned coupled wall boundary conditions.

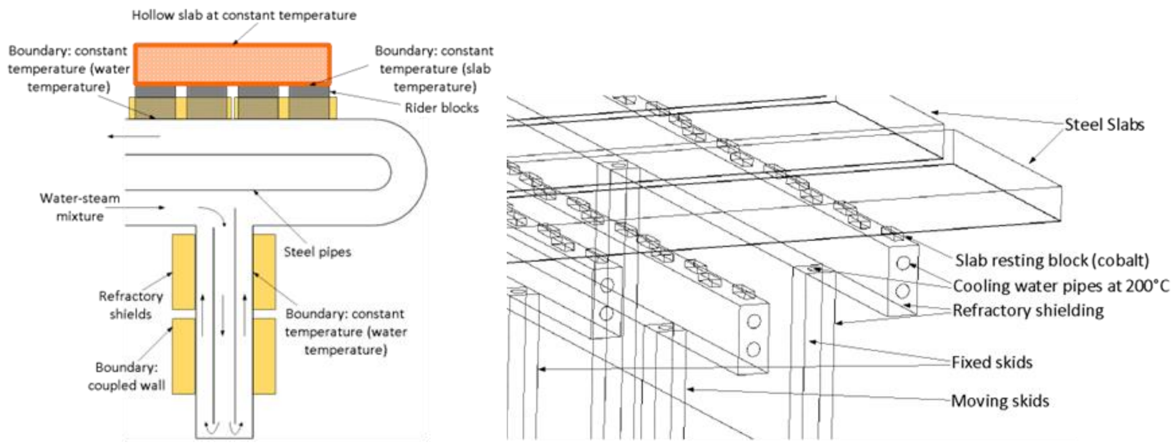

Figure 3 Schematic of the skid system and its implementation in the steady-state model

The furnace is typically loaded with slabs of different dimensions but in order to simplify the simulations, slabs of uniform dimensions are used and a total of 45 slabs are loaded inside the furnace. These slabs have a dimension of 9.7 m x 1.3 m x 0.22 m. In the steady-state model, these slabs are assumed to be thermally thin (or hollow) and a constant uniform temperature boundary condition is applied on them. This temperature is different on different slabs depending on their location inside the furnace. Figure 4 shows the assumed slab temperature for the slab along the length of the furnace. The emissivity of the steel is taken as 0.6. Scale formation on the slab surfaces are neglected but it is important to mention that the slabs have a slightly higher emissivity than that of pure steel without scale.

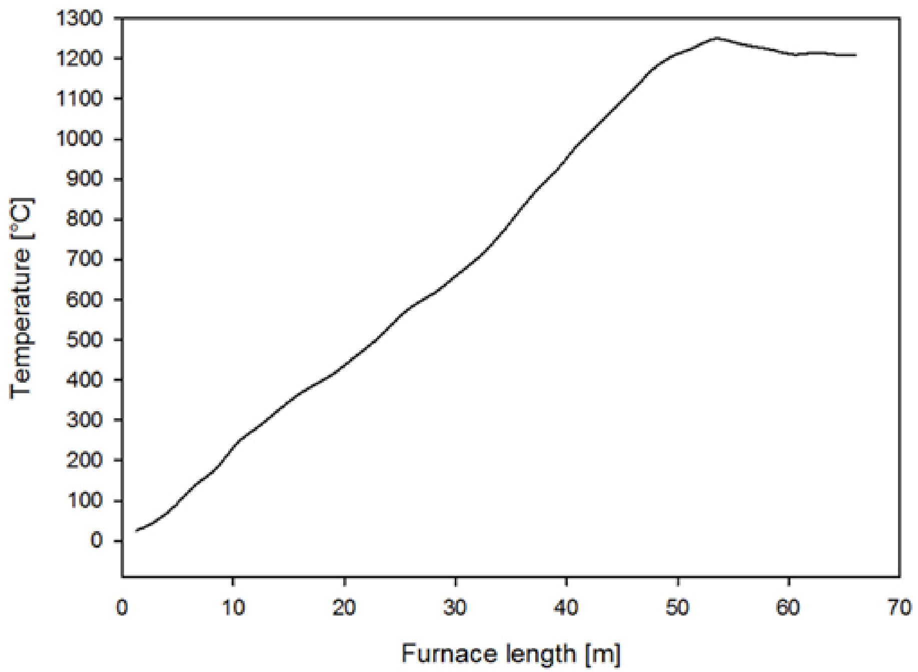

Figure 4 Assumed slab temperature profile

Burners of different capacities are installed in the different zones of the furnace depending on the temperature requirements of the zones. The burner flow rates and fuel gas compositions are logged for each of these burners. The preheating zone houses the regenerative burners, the heating zones are equipped with high power flameless burners and the soaking zone has many low power roof burners which are designed for maintaining the slab dropout temperature [2]. The burners in the heating and soaking zones operate on a mix of natural gas and coke oven gas while the regenerative burners work on low-calorific blast furnace gas. The operation of the regenerative burners has been explained in detail in Ahmed et al. [9] The air for the flameless burners is pre-heated to about 250°C using the exhaust gases, while in the regenerative burners the heat exchangers attached to the burners preheat the fuel gas to about 520°C.

Combustion, radiation and turbulence models

The burners are the source of heat for the furnace, therefore suitable combustion and radiation models have to be used for accurately estimating the energy input and flame temperatures inside the furnace. The non-premixed combustion model is used to account for the combustion process and the Discrete Ordinate (DO) radiation model is used to account for the radiative heat transfer [13]. The k-epsilon model is used to account for the turbulence [14]. The weighted sum of grey gases model is used to calculate the absorption coefficients for predicting the radiative heat transfer from the medium [15].

Various material properties are obtained from the data sheets of ArcelorMittal. This includes the properties of steel, refractory material and the rider blocks. The thermal properties of the steel are considered unchanging in the steady-state model as conduction inside the steel slab is not modelled in it. Since all the refractory linings are multi-layered walls, mass averaged equivalent thermal properties are considered for the refractory material. The rider blocks are made of cobalt alloy (UMCo50) specifically designed to be wear-resistant and their thermal properties are included in the model.

Computational grid

The computational grid for the steady-state model consist of about 75 million cells. Various refinements have been carried out at locations such as the slabs, the rider blocks and the burners. Figure 5 shows the refinements carried out on the burners and the skid-slab contact areas.

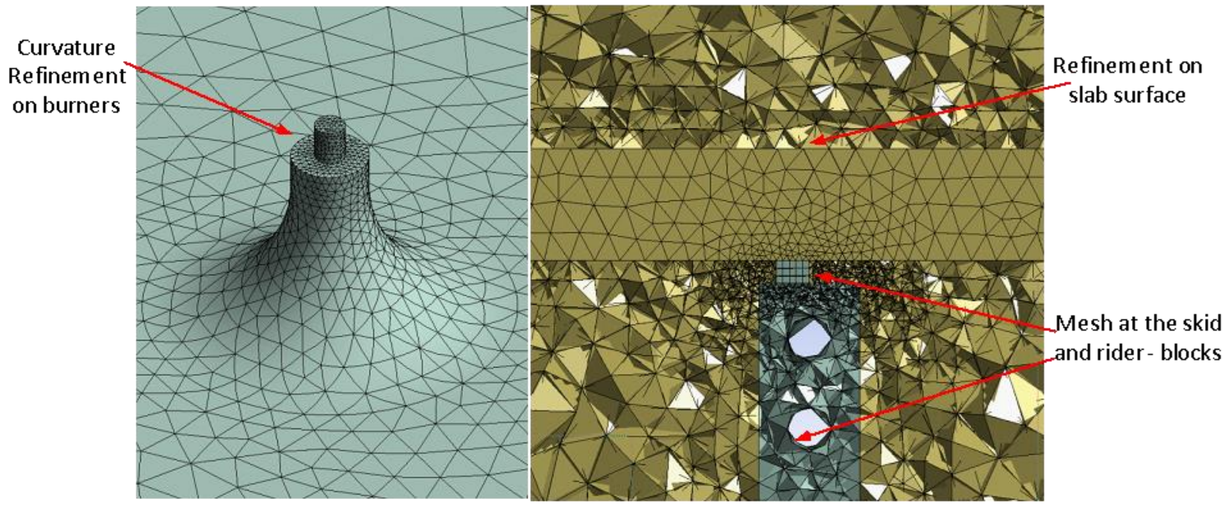

Figure 5 Mesh refinements in the Steady-state model

Results and Discussions

Model validation

The rationale behind using the steady-state approach has been motivated in the works of Ahmed et al. [2] and many others [14,13,16]. Validation of the furnace model has therefore involves the definition of operating temperature of the different zones inside the furnace. Figure 6 plots the maximum and minimum temperatures obtained for each of the zones using thermocouple measurements. The CFD model closely follows the ranges defined using the data. The data reduction process is also explained in detail in the works of Ahmed et al. [2].

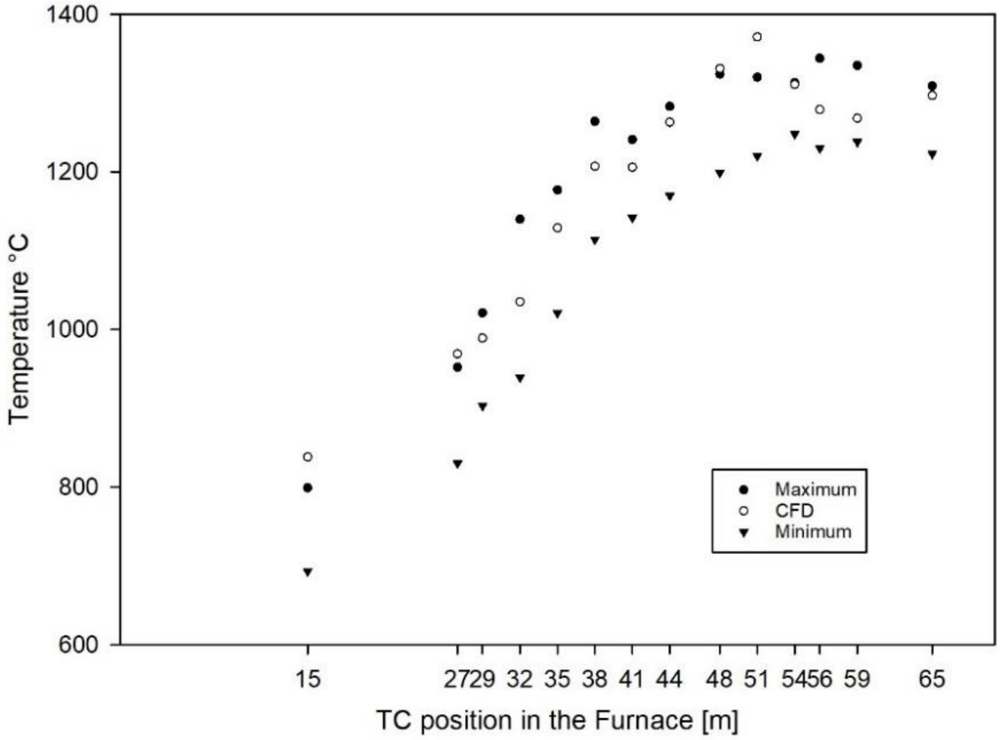

Figure 6 Validation of the steady-state model

Furnace characteristics

The influence of the skid coolant temperature is investigated by keeping all other operating conditions constant, while only the coolant temperatures are increased. This is evaluated on the furnace level by plotting the temperature distribution on the central plane of the furnace. They are then compared with the two cases where the coolant temperature is 200°C (base case) and 350°C (high temperature case).

Ahmed et al. [2] showed that the bottom half of the furnace is being cooled due to the presence of the water cooled skids. This drop in temperature also leads to a drop in heat fluxes on the bottom face of the slab compared to the top face. This drop in heat flux (especially in the pre-heating zone) is also attributed to the accumulation of the hot gases in the top half of the furnace. However in the heating and the soaking zones where there are burners in the bottom half of the furnace these effects are negligible. This has been shown to be the case in numerous articles in the available literature [5,6,7], however few to no studies can be found on the impact of changing the coolant temperature. Thus, the following sections aim to evaluate the impact of increasing the coolant temperature.

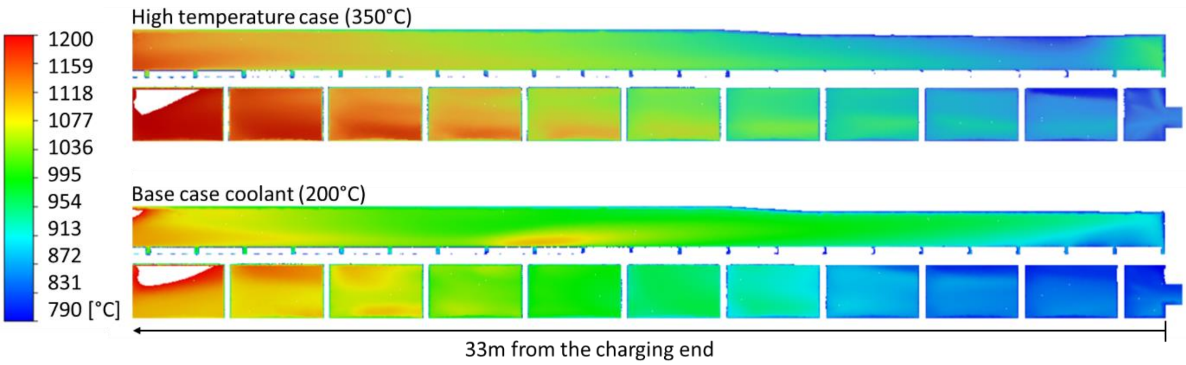

Figure 7 Cross-sectional temperatures along the central plane of the furnace

There are two cases analysed for the changing coolant temperatures, first the skid temperatures in the furnace have been set to its operational value of 200°C and in the second case both the soaking and heating zone skid temperatures are increased to 350°C. The furnace is currently operated at a skid-coolant temperature of 200°C, thus is the reference case with which the sensitivity of the skid coolant temperature will be assessed. The influence of the change of this temperature is evaluated on three aspects of the slab reheating process: on the furnace level, by comparing the changing temperatures due to the increased skid coolant temperature; on the slab level, by comparing the slab heat fluxes on the bottom surface of the slabs; and finally on the skid-slab contact, by evaluating the heat fluxes in those locations.

A central cross-sectional contour is plotted along the length of the furnace in Figure 7. The plot shows the first half of the furnace which is void of any burners. This is the zone of the furnace where the influence of the water-cooled skids is the highest. This is due to the fact that unlike in the soaking zone (where both the furnace and the slab are at about the same temperature), the pre-heating and heating zone accommodates slabs that are cooler than the zone itself. Therefore, the influence of a higher zonal temperature is a lot more prominent. Comparing the two cases, it is quite clear that the high coolant temperature increases the overall temperature in the preheating zone. This increase in temperature would certainly lead to an increase in heat fluxes on the slab surface, especially on the bottom face.

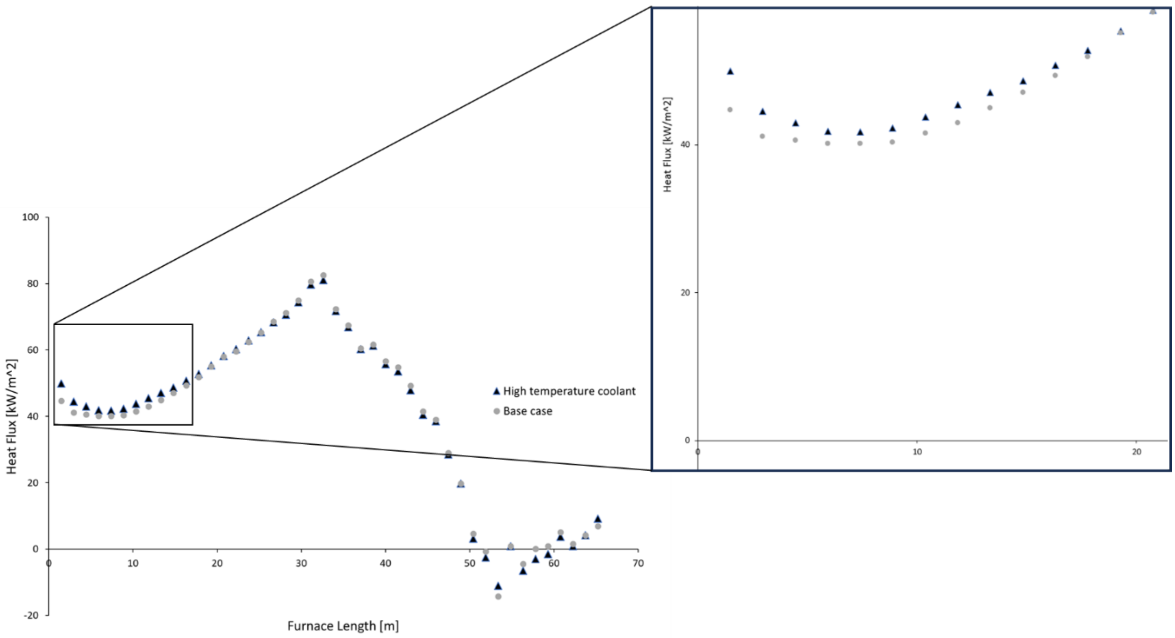

Figure 8 Average heat flux on the slab bottom face for changing skid coolant temperature

Figure 8 plots the evolution of the average heat fluxes on the slab bottom face for the two cases analysed. As expected the heating and the soaking zones show little to no change in the heat fluxes. This is because the slab surface temperatures in the heating and the soaking zones are already quite high and the slab heat fluxes in these locations are less susceptible to the changes in environmental temperatures. However, in the pre-heating zone the slab most certainly receives higher heat fluxes, this is shown in figure 8 with the zoomed-in view of the first 20m of the furnace length.

It can therefore be concluded that this increase in heat flux on the slab surface is due to the higher zonal temperatures, which would then result in higher slab temperatures in those locations compared to the base case. Since heat fluxes are the primary determining factor for effective slab reheating, it can also be assumed that with higher heat fluxes the reheating time will likely reduce.

Reheating time of a slab also depends on the residence time of the slab in the soaking zone of the furnace. The purpose of the soaking zone is to resolve temperature differences inside the slab. The hottest parts of the slab are the slab corners while the coldest parts of the slab are the skid marks. Skid marks are generated at the bottom of a slab due to the contact of the slab with the cold skids, which act as heat sinks. Increasing the coolant temperature also increases the temperature of the cold spots generated by the skid slab contact. Ahmed et al. [9,10] quantified the severity of the cold spots by defining the penetration depth of the cold spot inside the slab. It is defined as the depth at which the skid mark temperature reaches the centreline slab temperature. This result can only be obtained using a transient model, e.g. the heat-flux-based model by Mayr et el. [14] or the truncated model by Ahmed et al. [8,9].

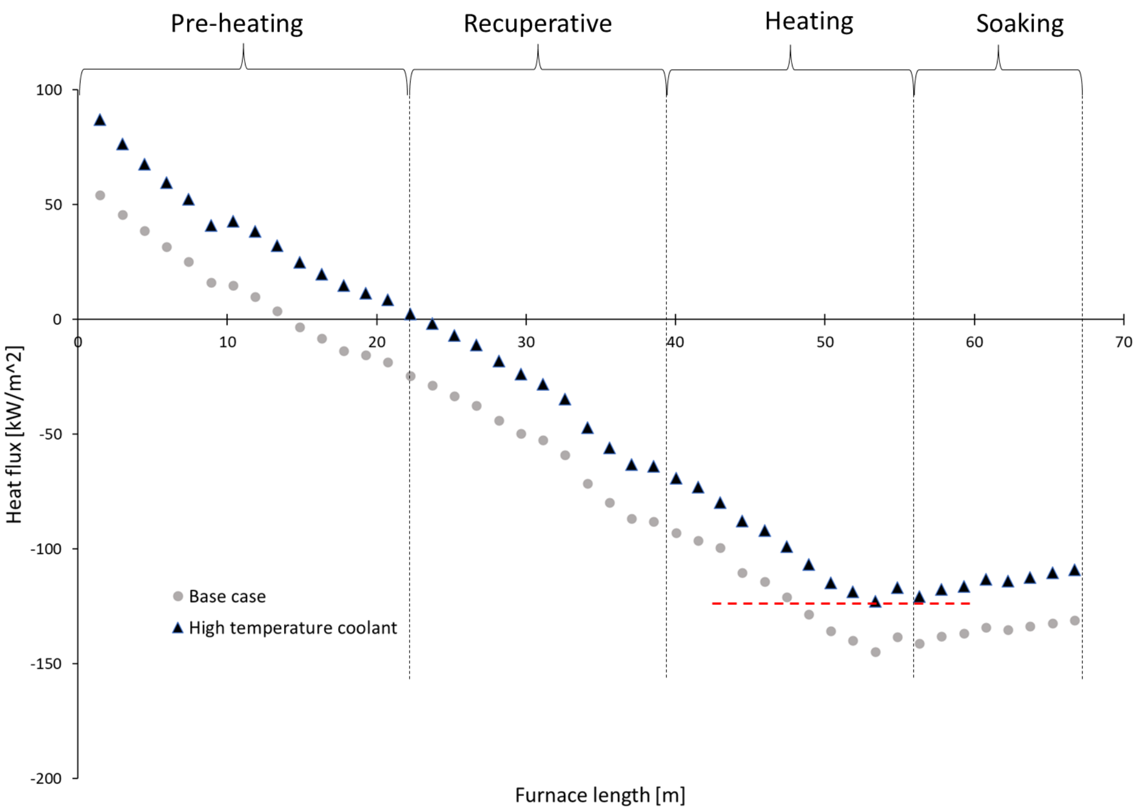

Figure 9 Average heat flux at the skid-slab contact points for changing skid coolant temperature

The main factor determining the cold spot temperature is the heat flux at the skid-slab contact. Figure 9 shows the evolution of this heat flux for the two cases analysed. As described in the section concerning the computational domain, the skids change position in the soaking zone. This is done to reheat the cold spots generated in the pre-heating and the heating zones.

The heat fluxes at the skid-slab contact determine the severity of the cold spots (viz. penetration depth). Figure 9 plots these heat fluxes along the furnace length at the skid-slab contact. The first observation is that the heat fluxes in the skid contact points are much lower compared to the base case. Another observation is that the skid actually heats the slab in those locations as it is hotter that the slab in the preheating zone. Beyond the pre-heating zone it starts to cool the slab at the contact locations. On comparing the two cases we see that the high coolant temperature case heats the slab till about 22 m while the base case does so till about 13 m of the furnace length. This is important because the longer the contact point cools the spot the deeper the spot penetrates (with the limit that the heat flux form the top surface is also heating the slab). The red dashed line also signifies the lowest fluxes subjected to the slab by the skids in the high temperature case. Compared to the base case this is the average heat flux at about 46m while in the high temperature case this value corresponds to a position of 55 m. It was also described in the section concerning the computational domain, that the skids change position in the soaking zone. This is done to reheat the cold spots generated in the pre-heating and the heating zones. In the high temperature case we see that the cooling of the contact point is offset by about 9 m of furnace length. This corresponds to about 42 minutes of residence time where the cold spot is not cooled (this should however not be interpreted as a saving of 42 minutes of reheating time). Therefore, it would definitely take less time to reheat these spots in the soaking zone. It can also be seen that the contact heat fluxes in the high temperature case in the soaking zone are lower compared to the base case. Combined with the lower residence time in this zone it results in less severe skid marks in the soaking zone compared to the base case. As previously mentioned, a thorough analysis of this effect requires a transient model, which will be the topic of future work. This is work even without a transient model shows significant prospects for saving in the reheating time of the slabs and thereby resulting in energy saving in the slab reheating process.

In conclusion, it should be noted that the results presented in this paper should not be taken as an absolute measure of the temperature rise in the furnace or increase in heat fluxes on the slab level. The steady-state model is an approximation of the real operating furnace, as such it is dependent on the boundary conditions of the furnace. In this case the constant slab temperature boundary condition has a significant influence on the furnace temperature (and slab heat flux). Therefore, Figures 7, 8 and 9 only serves as a proof of concept that increasing the skid-coolant temperature would lead to the better performance of the furnace. In order to quantify the increased performance, the actual slab temperatures have to be calculated either by using the heat-flux based model (Mayr et al.[14]) or by using the truncated model approach (Ahmed et al. [8,9]). Once the steady-state model and the transient models (heat-flux-based or truncated model) are iterated with the correct slab temperatures, and penetration depths of the cold spots the exact performance gains of the furnace can be quantified.

Conclusion

This studies a very specific aspect of the slab reheating process in a reheating furnace. It assesses the possibility of changing the coolant temperature of the water-cooled skids in order to understand its impact on the reheating process. This impact is divided into two aspects, first the influence on the furnace level and second on the slab level. It is clear from the analysis that the average temperature in the bottom half of the furnace increases, leading to an increase in the heat fluxes on both the bottom surface of the slab, and reduced cooling at the skid slab contact points. It is seen that the high heat fluxes are especially prevalent in the pre-heating zone due to a larger difference between the slab surface temperature and the furnace environment. On the skid-slab contact level, the heat fluxes are much lower compared to the base case. This results in a shallower skid mark (viz. penetration depth) which is easier to reheat in the soaking zone, thereby lowering the residence time in that zone. Combined with the higher heat fluxes the slab receives in the pre-heating zone and the shallow skid marks and the higher heat fluxes at the contact points, the proposed increase in the skid coolant temperature could lead to substantial gains in the reheating time of a slab. However, to exactly quantify the gains a transient model needs to be employed.

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