INFLUENCE OF SIMPLIFICATION OF THERMOPHYSICAL PROPERTIES ON COMPUTATIONAL MODELING OF HEATING PROCESS OF STEEL BILLETS IN PUSHER-TYPE REHEATING FURNACE

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https://doi.org/10.37904/metal.2023.4699

Abstract

This article focuses on the influence of simplification of thermophysical properties on computational modelling of heating process of steel billets in pusher-type reheating furnaces. The objective is to investigate the impact of the simplification of thermal conductivity and heat capacity on the temperature gradient within the material surface and the centre. The pusher-type reheating furnace is widely used in the steel industry for the reheating of steel billets before they are processed further. The heating process is complex, involving the transfer of heat from the combustion gases to the steel billets, and the temperature distribution within the material plays a critical role in determining the final quality of the product.

The study uses a computational fluid dynamics (CFD) model to simulate the heating process of the steel billets, and the effects of simplification of thermophysical properties are analysed. The results show that the simplification of thermal conductivity and heat capacity leads to a significant overprediction of the temperature at the material surface, resulting in a higher temperature gradient between the surface and the centre of the billet. The simplified models also show a poor correlation with the experimental data.

The study concludes that the simplification of thermophysical properties can result in significant errors in the computational modeling of the heating process of steel billets in pusher-type reheating furnaces. It is therefore recommended to use more accurate thermophysical property models to improve the accuracy of the simulation results. The study also highlights the importance of experimental validation of the computational models to ensure their accuracy and reliability in predicting the temperature distribution within the material.

Keywords: Reheating furnaces, steel properties, computational modelling

1. INTRODUCTION

Heating furnaces are used in steel mills to heat steel semi-finished products (such as slabs, blooms, or billets) to rolling temperatures suitable for plastic deformation of steel and therefore for rolling in the mill. The heating process in the heating furnace is a continuous process, in which the steel material is inserted into the furnace at the inlet, heated in the furnace, and discharged at the outlet of the furnace. Heat is transferred to the steel material mainly by convection and radiation from the burner gases and furnace walls as it passes through the furnace.

The pusher-type reheating furnace gets its name from the mechanism used to push the steel through the furnace. It consists of a long, rectangular furnace chamber with multiple heating zones. The steel is loaded onto a charging table at one end of the furnace, and a pusher mechanism pushes the steel billets or slabs one by one into the furnace chamber.

Inside the furnace, burners or heating elements generate high-temperature heat, typically using natural gas or fuel oil as a fuel source. The burners are placed in different zones along the length of the furnace to provide controlled heating. The steel moves through these heating zones, gradually increasing in temperature.

The pusher mechanism advances the steel through the furnace at a controlled speed, ensuring that the steel spends enough time in each heating zone to reach the desired temperature uniformly.

Pusher-type reheating furnaces are designed to provide efficient and uniform heating, minimizing temperature variations within the steel. This uniform heating is crucial for achieving consistent mechanical properties and dimensional accuracy in the final steel product.

Generally, heating of semifinished products (billets) require solution of heat balance between external heat flux and enthalpy of the heated body [1,2]:

$$q \cdot A \cdot d\tau = m \cdot c_p \cdot dt \tag{1}$$

where:

- q - the heat flux density ($W \cdot m^{-2}$)
- A - area (m^2)
- $d\tau$ – differential of time (s)
- m - mass (kg)
- c_p – specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
- dt – differential of temperature (K)

As every differential equation solving requires knowledge of conditions of monovalence – geometrical (shape and dimensions), physical (material properties), initial (temperature at the beginning of process) and boundary (heat flux density, or temperature of furnace walls and atmosphere composition).

There are many ways how to solve this problem, classic solution based on [1] is applied and verified by measurement is in [3]. So-called zonal method applied for reheating furnaces is in [4–7], which are much more complex as they take into account the balance between heated material, furnace atmosphere and walls and adjacent zones - the energy conservation rule is valid for all surface and volume zones, and the energy balance equations can be given for each zone as the zone temperature is regarded to be the unknown. With development of computational fluid dynamics (CFD), conjugated heat transfer models with coupled fluid flow emerged, but they become still to computationally demanding [8-10]. Combination of 3D CFD model with 2D heat transfer model was used in [11]. Coupling of two different models was used by authors of [12]: a steady-state model of the complete furnace and a transient model of the truncated domain around a single slab. The truncated domain replicates the flow conditions of a full-scale transient model in a much smaller domain. For optimization of existing furnaces with historical data genetic algorithms can be used [13]. Neural networks of different architectures can be also used for modelling purposes [14], deep learning techniques seems to work as well [15]. Models based on machine learning [13-15] does not solve equation (1) at all, but works with probability predictions based on historical data.

Presented work uses classical approach [1] for determining the boundary conditions in the furnace and ANSYS Fluent for computing of transient temperature field within billets. Moving billets in computational domain is replaced by „moving“ boundary condition. The task was to figure out whether neglecting of temperature dependence of the material properties have significant effect on the results as some studies work with constant properties as it makes computation faster.

2. STUDIED CASE

Computation deals with a case of heating of billets with dimensions 160×160×4,300 mm in a pusher type reheating furnace with three zones: preheating, heating and soaking zone. Chemical composition of reheated steel is in **Table 1**. Initial temperature of billets is 10 °C, demanded temperature is 1,300 °C.

These assumptions are applied:

Temperature distribution along the length of the billet is uniform, so the differential equation is simplified to two-dimensional unsteady heat conduction and moving speed of the billet is uniform in every zone. Geometry and initial temperature of the billet are known.

Table 1 Chemical composition of the steel billets

Element	C	Mn	Si	P	S	Cu	Ni	Cr
wt%	0.08	0.73	0.196	0.016	0.014	0.08	0.02	0.05

2.1 Furnace

The scheme and dimensions of the furnace are in **Figure 1** material comes from left to right. Heating zone is both top and bottom fired, soaking zone is only top fired. Furnace is fired by mixed gas based on coke oven gas, blast furnace gas and natural gas. Furnace reheating capacity is 45,000 tons per hour. Regulation of mixing the gases is based on constant Wobbe number. Average chemical composition of mixed gas in **Table 2**, average lower calorific value of fuel is 7.5 MJ·m^{-3}**,** overall air to fuel ratio is 1.2. Combustion air is preheated to 215 °C. **Figure 2** represents heat flux density along the furnace computed based on furnace geometry and operational data. It was used as a boundary condition for simulation in SW ANSYS Fluent.

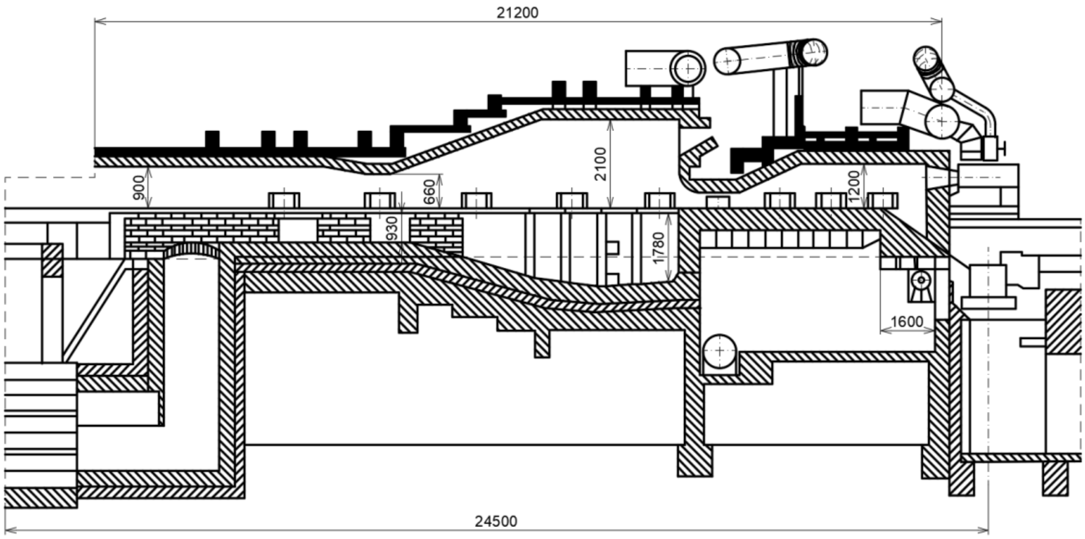

Figure 1 Examined pusher type reheating furnace

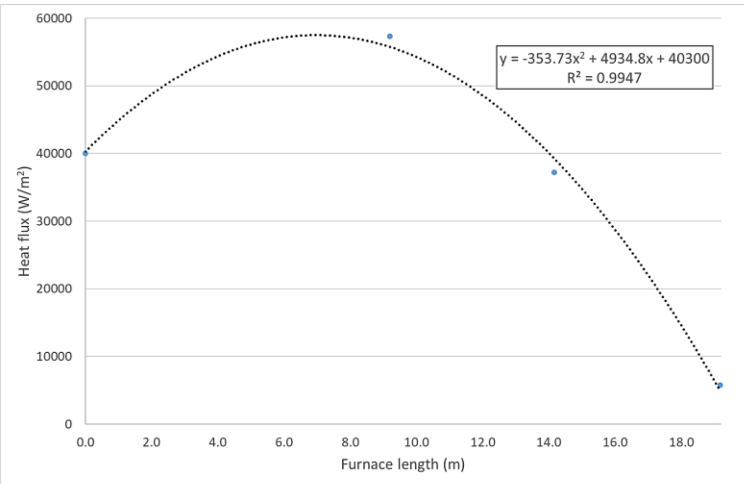

Figure 2 Heat flux along the furnace

2.2 Case A – constant material properties

Material properties of for case A are in the **Table 2**:

Table 2 Average material properties for expected mean temperature during heating (655 °C)

Density ($kg \cdot m^{-3}$)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
7843.6	29.78	579

2.3 Case B – temperature dependent material properties

As computational model works with rigid computational mesh for solid zone, using temperature dependent density makes no sense and is not allowed, therefore the same value of density was used. **Figure 3** shows specific heat as a function of temperature divided into three temperature intervals as the course of dependence cannot be fitted with one single function. **Figure 4** shows temperature dependence of thermal conductivity fitted with two linear functions of temperature.

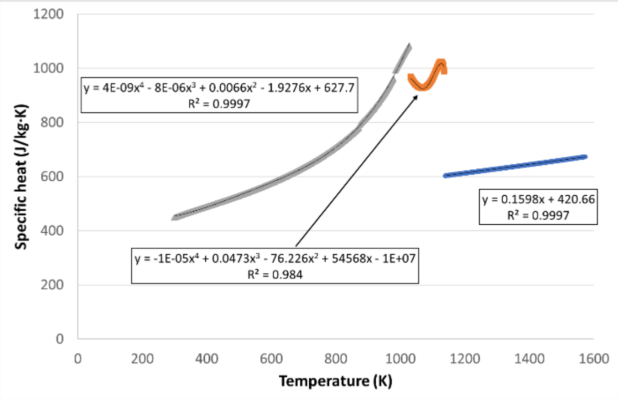

Figure 3 Specific heat

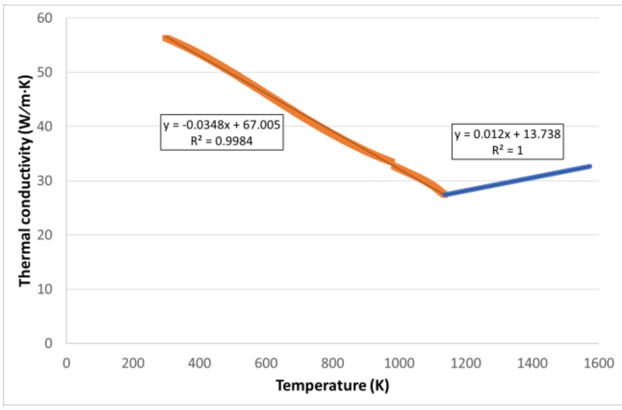

Figure 4 Thermal conductivity

Both thermal conductivity and specific heat was calculated by JmatPro software which allows computation of material properties for simulations in metallurgy and material engineering [16].

2.4 Results

Figure 5 displays temperature evolution of surface and centre of billet.

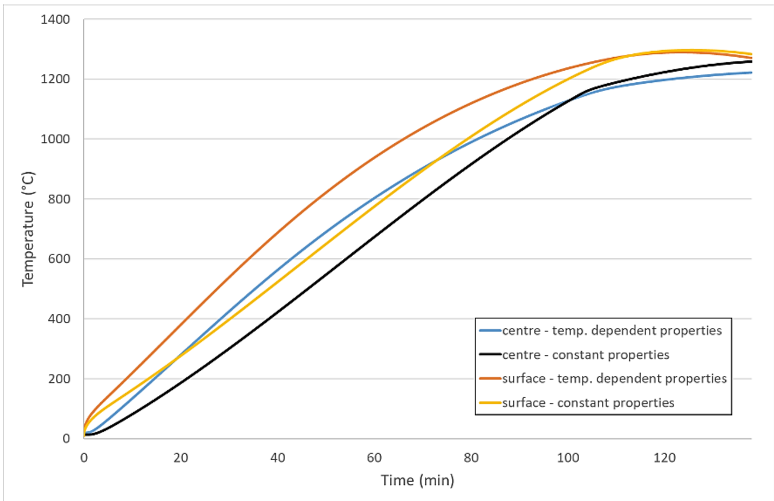

Figure 5 Temperature profiles within a billet

Both approaches, with constant and temperature depending material properties led to temperatures below demanded one. Final temperatures and temperature difference between surface and centre are in **Table 3** also compared with measured surface temperature at exit measured with a pyrometer. Verification by continuous temperature measurement either with trailing thermocouples or thermobox is time and financially demanding so it is rarely used.

Table 3 Temperatures (°C) resulting from simulation at exit from furnace

	Centre	Surface	Δt	Measured surface temperature	Deviation
A - constant properties	1,245	1,283	38	1,240	43
B - temperature varying properties	1,198	1,271	73		31

Even though required temperature (1,300 vs 1,240 measured) was not met, results show that using of constant material properties leads to underestimation of heat rate in the beginning of the heating and overestimation in the second half of heating. This can lead to problems with too fast heating of cold material under temperatures where steel is plastic and can cause a mechanical damage due to thermal stress. Another problem can be false information – underestimation of temperature gradient within the heated body at the end of the heating which can cause problems during rolling of the semifinished products into final shape.

3. CONCLUSION

It has been proved that knowledge of material properties varying with temperature is important as simplification of calculation using constants can lead to significant deviations in obtained results and underestimation of potential problem during manufacturing. Presented case showed that simplification led to underestimation of temperature gradient between surface and centre and to higher deviation between measured and computed surface temperature. As the quality of product is crucial, one should avoid any unnecessary simplification during modelling or designing of control system. The same principle applies not only to process in reheating furnaces but also for furnaces for thermal treatment.

ACKNOWLEDGEMENTS

Work was supported by a project SP2023/034 - Research and development of composite multifunctional materials for sustainable progress.

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