Application of Finite Element Method based simulations and metamodeling techniques for prediction of liquid steel cooling rate in main ladles

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1. Introduction

Measurements of temperature distribution of liquid steel inside a ladle is very difficult or sometimes even impossible task in industrial conditions, due to the safety reason and high cost of equipment. On the other hand precise knowledge about the overheating level is crucial to maintain optimal range of temperatures during Continuous Steel Casting process to obtain the highest quality of casted billets.

This paper is focused on the description of the system for the real time prediction of the liquid steel temperature in the ladle based on the FEM model. Results of simulations were verified with measurements performed in the production line, which were filtered using the Weibull distribution. It was shown that the model correctly predicts the temperature of liquid steel. The mean relative error of the calculations was in the range: 0.12–0.18.

1.1. Numerical model

Model describes the heat transfer in molten steel during transport of the ladle between the stations: refining - tundish. Scheme of the ladle was shown in Figure 1, while both its shape and dimensions correspond to the real ones. The side wall of the ladle consists of three layers of different materials in order to meet specific mechanical and thermal requirements: steel shell (1), safety insulation layer (2) and working lining (3), the thicknesses of which are 0.028, 0.101, and 0.203 m, respectively. The weight of the molten steel was 150 tons. Input data, including: temperature of molten steel measured after the refining process, temperature of ladle armor and transport time, were received from the monitoring system.

The values of the thermophysical parameters introduced into the model are summarized in Table 1. The data for the lining came from the material cards. The thermal conductivity coefficient *l* of the slag was determined on the basis of experimental studies. The specific heat and emissivity data for each of the materials were literature data [1,2].

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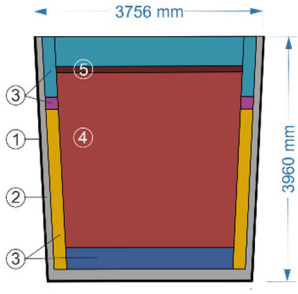

Figure 1. Scheme of the ladle furnace: 1– armor, 2 – insulation layer, 3 – lining, 4 – molten steel, 5 – slag.

Table 1. Thermophysical parameters.

Material		Temperature	Density	Thermal conductivity	Heat capacity	Emissivity
		°C	ton/mm³	W/mm·K	J/ ton·K	—
Ladle armor		measurement	$7.80 \cdot 10^{-9}$	$5{,}20 \cdot 10^{-2}$	787 000	0.8
Insulation		1 000	$2.75 \cdot 10^{-9}$	$9{,}50 \cdot 10^{-4}$	1 056 000	0.75
Lining	ANCARBON C S1T12-EU	1 100	$2.96 \cdot 10^{-9}$	$8{,}00 \cdot 10^{-3}$	800 000	0.75
	SYNCARBON C F7T05P	1 100	$3.04 \cdot 10^{-9}$	$6{,}00 \cdot 10^{-3}$ (1 000°C) $5{,}00 \cdot 10^{-3}$ (1 200°C)	800 000	0.75
	SINDOFORM C-EU	1 100	$2.90 \cdot 10^{-9}$	$3{,}00 \cdot 10^{-3}$	800 000	0.75
	SINDOFORM C5-EU	1 100	$2.88 \cdot 10^{-9}$	$3{,}50 \cdot 10^{-3}$	800 000	0.75
Molten steel		measurement	$7.10 \cdot 10^{-9}$	$4{,}10 \cdot 10^{-2}$	750 000	—
Slag		measurement	$3.81 \cdot 10^{-9}$	$1{,}21 \cdot 10^{-2}$	838 000	0.8

The FEM solution of the Fourier equation (1) was carried out in the 2D system using Abaqus.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) \tag{1}$$

where: ρ – the material density, c_p – the specific heat of the material, k_x, k_y – coefficient of heat conduction of material.

The following boundary conditions were assumed in the model: the temperature of the inner surface of the ladle is equal temperature of the molten steel, heat transfer inside liquid steel, insulation layer and lining carried out by conduction, heat transfer from the outer surface of the ladle and the slag layer occurs by convection q_c and radiation q_r (2).

$$\begin{aligned} q(y,t) &= q_c(y,t) + q_r(y,t) \\ q_c(y,t) &= \lambda(T_e(y,t) - T) \\ q_r(y,t) &= \varepsilon\delta(T^4(y,t) - T_e^4) \end{aligned} \tag{2}$$

where: λ – convective heat transfer coefficient, ε – emissivity, δ – Stefan-Boltzman constant, T_e – ambient temperature.

2. Results

Numerical simulations were carried out for the following steel grades: B500SP, S355J2, S235JR, STRETCH500, B500B, C45E, 30MnB4, 16MnCr5. The temperature distribution in the molten steel is presented in Figure 2. In all the analyzed cases, the temperature drop was observed only under the slag layer and in the contact zone with the ladle lining.

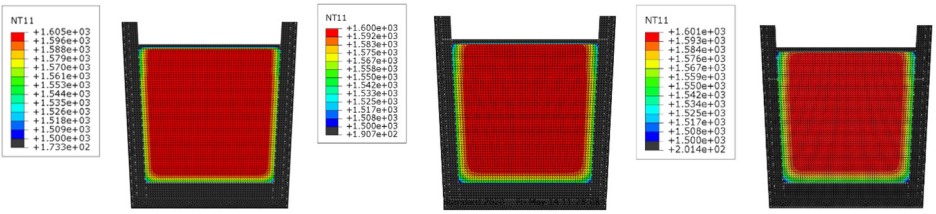

Figure 2. Temperature distribution in the molten steel – 16MnCr5 steel: a) melt I – 1587°C, 19 min, b) melt II – 1570°C, 18 min, c) melt III – 1607°C, 10 min.

The obtained results were compared with measurement data from the process monitoring system (Figure 3). The data was filtered using the Weibull distribution [3], because reliability tests have shown that 6.5% of the data is burdened with a gross error. The cooling rate varied within the range of 1.18°C/min for STRETCH500 steel and 1.39°C/min for 16MnCr5 steel. The mean relative error of the calculations was in the range: 0.12–0.18.

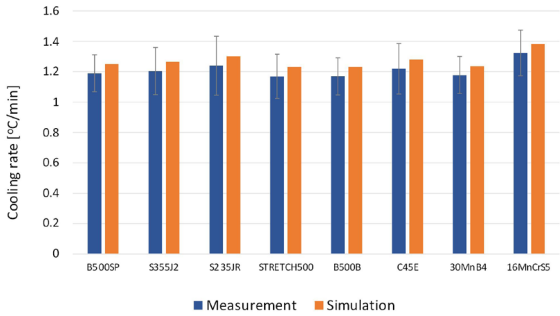

Figure 3. Cooling rate of liquid steel – comparison of calculated (orange column) and filtered measurement data (blue column).

3. Conclusions

The model allows the determination of liquid steel cooling rate in main ladle. Measurements of temperature in the tundish confirm the correctness of the model. Due to the long computation time ~35 min, it is necessary to create a metamodel that will enable the use of the prediction model in industrial conditions.

References

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