Steady mathematical model of ladle furnace heat work

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Abstract This paper presents the mathematical model of ladle furnace heat work, which is based on the heat balance equation of the furnace. The model was created based on data from the operating unit. There are considered the three stages of melting: deoxidation, desulphurization and alloying. Duration of the process is long, so it can be considered as quasi-steady process. It works with heat summation values in various stages of melting. Items in the heat balance include, except for the heat contained in the steel and slag, the heat of electric arc, furnace wall heat loss, the heat loss of furnace roof water-cooling, heat conduction losses through the electrodes, exothermic and endothermic heat reactions of ingredients and the heat loss of outgoing gases. The model can be used for energy and economic calculations and for the ladle furnace control.

1 Introduction

Technologically, ladle furnaces are situated before continuous casting of steel, therefore processing time in the ladle furnace is influenced by the need for metal in the continuous caster. The control of melting in the ladle furnace depends on many parameters. Temperature regime of melting is one of the priority effects. It is necessary to have a thorough idea of how much heat is generated and what are the heat losses in the ladle furnace in order to achieve the desired temperature at the end of melting metal. Ladle furnaces consume a large amount of electrical energy and are sensitive to overheating. Excessive overheating of metal increases the relative power consumption as well as linings wear. Therefore it is necessary to control the furnace to keep the temperature of steel in a specific narrow temperature range.

2 Methodology of the solution

The mathematical model was constructed, based on the thermal balance of the ladle furnace. A summation of heat losses during melting is calculated [1, 2]. Two groups of heat losses were considered: variable losses and steady losses for the entire heat.

Three stages of melting are considered: deoxidation, desulphurization and alloying. Heat balance equation for each stage of the process of melting is as follows. Index *n* figures a number of the stage and varies from 0 to 3.

$$Q_n^{\mathrm{metal}} + Q_n^{\mathrm{slag}} + Q_n^{\mathrm{st}} + Q_n^{\mathrm{var}} + Q_n^{\mathrm{arc}} = Q_{n+1}^{\mathrm{metal}} + Q_{n+1}^{\mathrm{slag}} \tag{1}$$

where Q^{metal} is steel thermal energy at the beginning or end of the stage (J),
Q^{slag} – slag thermal energy at the beginning or end of the stage (J),
Q^{st} – steady heat losses during the stage (J),
Q^{var} – the sum of variable heat losses during the stage (J),
Q^{arc} – energy of arc heating of steel and slag (J).

The total steady heat loss consists of losses through the lining, the water-cooling of furnace roof and conduction through the material of electrodes. Heat loss through the lining is calculated as steady heat conduction with surface conditions of the 3rd type, including convection and radiation from the wall. Convection depends on the orientation of the wall [3, 4].

$$P_{\mathrm{lin}} = \frac{\pi \cdot h \cdot (t_{\mathrm{met}} - t_{\mathrm{amb}})}{\sum_{i=1}^{4} \frac{1}{2 \cdot \lambda_{\mathrm{i}}} \cdot \ln\left(\frac{r_{\mathrm{i+1}}}{r_{\mathrm{i}}}\right) + \frac{1}{2 \cdot r_4 \cdot K_1 \cdot \sqrt[4]{t_{\mathrm{surf1}} - t_{\mathrm{amb}}}}} + \varepsilon \cdot \sigma \cdot (T_{\mathrm{surf1}}^4 - T_{\mathrm{amb}}^4) \cdot S_{\mathrm{sw}} + \left(\frac{t_{\mathrm{met}} - t_{\mathrm{amb}}}{\sum_{i=1}^{4} \frac{\delta_{\mathrm{i}}}{\lambda_{\mathrm{i}}} + \frac{1}{K_2 \cdot \sqrt[4]{t_{\mathrm{surf2}} - t_{\mathrm{amb}}}}} + \varepsilon \cdot \sigma \cdot (T_{\mathrm{surf2}}^4 - T_{\mathrm{amb}}^4) \right) \cdot S_{\mathrm{bott}} \quad (\mathrm{W}) \tag{2}$$

where t_{met} is temperature of metal (°C), t_{amb} is ambient temperature of surrounding atmosphere (°C), h is height of the ladle (m), ε is emissivity (1), λ is heat conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$), σ is Stefan-Boltzmann constant ($\mathrm{W \cdot m^{-2} \cdot K^{-4}}$), δ is wall layer thickness (m), K is experimental coefficient for determination of heat transfer coefficient (1), r is radius of layer for vertical wall (m), S_{SW} is area of side wall ($\mathrm{m^2}$) and S_{bott} is area of ladle bottom ($\mathrm{m^2}$).

Temperature of input cooling water into the roof is 25-30 °C. Water temperature at the outlet from the cooling system must be below 40 °C to prevent salt deposits formation on tube walls.

Temperature difference between the lower and upper parts of electrodes causes heat loss flow. The calculation is carried out using Fourier equation [4]. Heat loss flow for a single electrode is equal to

$$P_{\mathrm{el}} = \frac{k \cdot \lambda_{\mathrm{aver}} \cdot \Delta T \cdot S_{\mathrm{el}}}{l} \quad (\mathrm{W}) \tag{3}$$

where k is the material and shape coefficient of the electrode (1), λ_{aver} is average heat conductivity of the electrode ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$), ΔT is temperature difference between upper and lower part (K), l is a distance between upper and lower positions of temperature measurement points on the electrode (m), S_{el} is electrode cross section area ($\mathrm{m^2}$). Heat loss Q (J) is then determined by multiplying the power loss P (W) over time.

Flue gas heat losses are variable in nature. They are characterized by volume and temperature of the gas-dust mixture. This mixture consists of argon used for metal mixing and homogenizing, nitrogen for sealing the roof, metal dust, water and carbon dioxide emissions which are arising from limestone. The calculation is carried out in mass units because heating causes a substantial expansion of the gas phase; the calculation of the volumes would be difficult.

Each agent can have different behaviour in the steel. Important characteristic of agent is the temperature of melting and reaction capacity with oxygen. Temperature determines the dynamics of the melting process. Adding ingredients into the ladle furnace causes thermal effect due to heating and melting, decomposition of metal compounds of ingredients, stirring with steel and slag, oxidation and metal transition into the slag [5, 6]. The mean value of metal oxidation factor for each stage was taken in the model.

3 Experiments and results

The model was implemented in a spreadsheet. The calculation was performed for the selected melting. The **Fig. 1** shows a diagram of steady heat losses. The largest heat loss occurs by cooling the furnace roof. Metal temperature drop due to steady heat losses is about 1 K per minute.

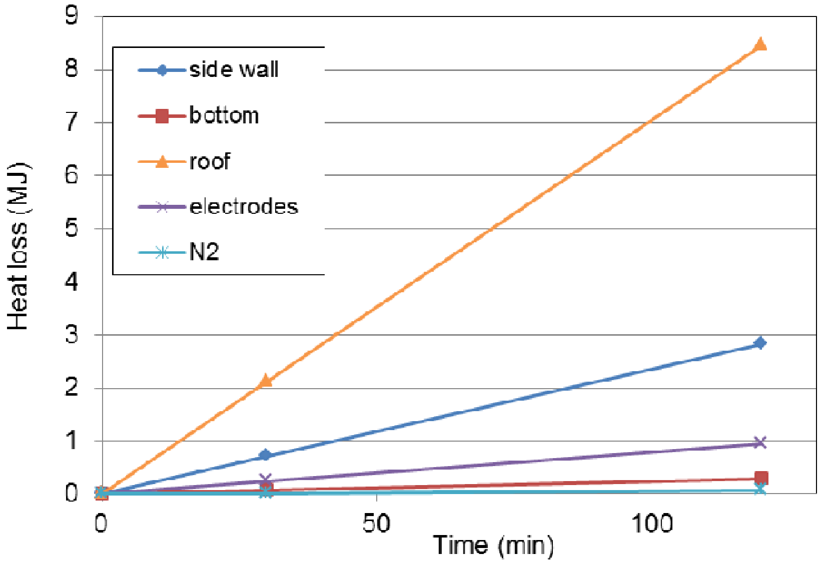

Fig. 1 Comparison of steady heat losses.

As considered the ingredients, the largest heat losses are caused by the slag-forming agents that are characterized by chemical inertness against steel. Relatively smaller heat losses arise from the formation of refractory and meltable alloys of iron. The graph in **Fig. 2** allows comparing the thermal effect of individual ingredients. In this case, dynamic characteristics of melting and assimilation of the ingredients in steel and slag are unknown. This effect depends on the fractional physical properties of ingredients, temperature and dynamics of the process. We take the maximum theoretical response time when analysing the model.

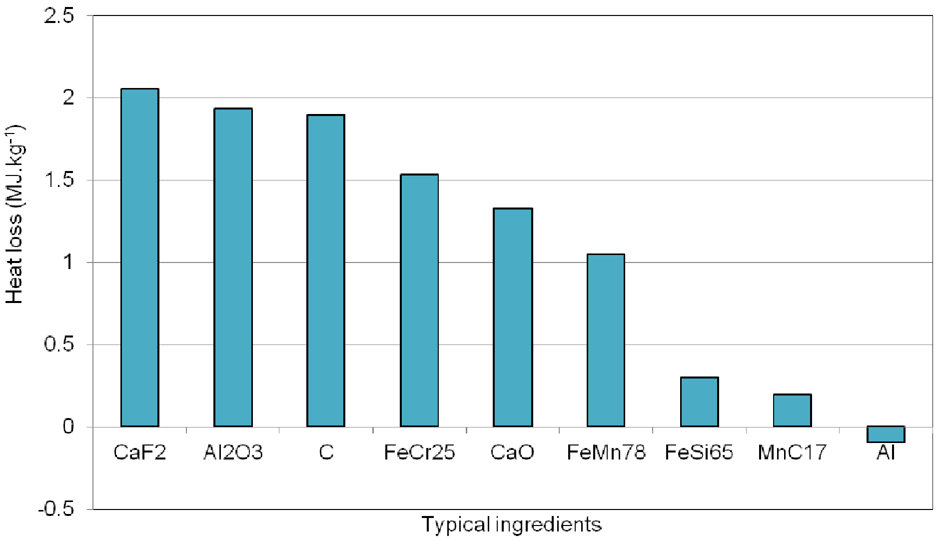

Fig. 2 Heat losses caused by various types of ingredients.

The diagram of heat losses for the entire cast is shown in **Fig. 3** The total amount of energy losses in the selected melting was about 27 000 MJ. More than half of the thermal energy is lost through the furnace roof.

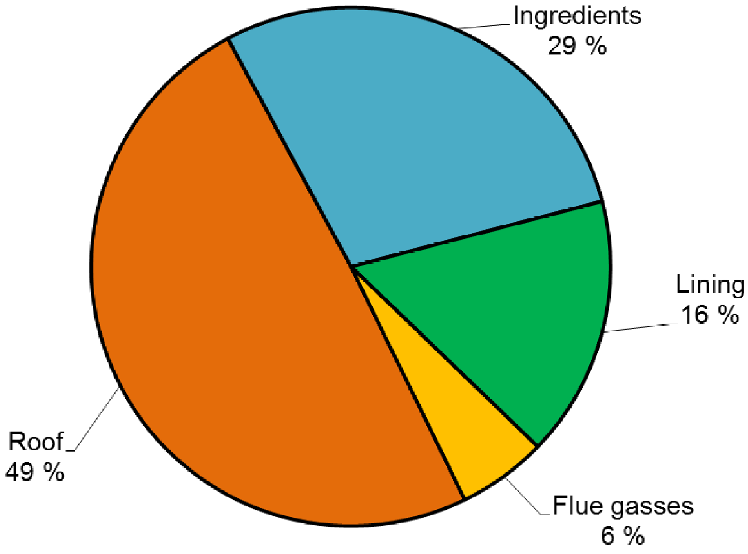

Fig. 3 Example of the total heat loss components of the ladle furnace.

4 Conclusion

Calculations show that the steady heat balance model of a ladle furnace is usable in practice. It is necessary that the adjustable parameters in the model were adapted to specific conditions of the concrete ladle furnace. The model can be beneficial for the techno-economic analysis and control of ladle furnaces. The next step will be to build a dynamic model which requires, however, knowledge of the dynamic coefficients of melting and assimilation of ingredients.

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