Mathematical Modelling of the Thermal State of a Ladle During Arc Heating of the Melt

E B Agapitov, M S Sokolova and M A Lemeshko
Department of Heat and Power Engineering Systems, Nosov Magnitogorsk State Technical University, 38, Lenin Street, Magnitogorsk, 455000, Russia

E-mail: margo88k2017@gmail.com

Abstract. The paper analyzes energy losses in the ladle furnace. In particular, the authors focus on electrical losses, namely total energy losses of the electric arc, conditionally including radiation losses of a part of the arc uncovered by slag. Managing these flows creates conditions for increasing the efficiency of heating. The calculations given in the paper showed that electrical losses decreased, during prolonged heating (about 8-12 minutes) with a sufficient amount of slag. This mode provides a reduction in heat loss by 4-5 %. By selecting options of changes in a sequence of stages and their duration, the proposed mathematical model makes it possible to apply a new technology to process molten steel in the ladle furnace characterized by lower power consumption.

1. Introduction
A higher quality and better technical and economic performance of steelmaking units and continuous casting machines are mostly provided by secondary metallurgy. Currently, existing ladle treatment facilities are characterized by relatively low thermal efficiency and, at the same time, a great potential for saving energy and electricity.

A ladle furnace is an intermediate link between a steelmaking unit and a continuous casting machine and ensures their coordinated operation. There are frequent situations in production when neither the thermal state nor the chemical composition of steel in terms of the ladle volume is known at the starting time of treatment [1, 2]. At the same time, the uneven temperature of the melt reaches 40-50 °C by weight and local measurement data with a single immersion thermocouple are not indicative of bulk temperature of the melt, resulting in errors in temperature setpoints for casting the melt on a continuous casting machine [3].

The efficiency of heating the melt is determined by power of the electric arc unit, which is, in its turn, determined by transformer power. When applying alternating current, power should be optimal for a given volume of steel and the geometric dimensions of the ladle. When transformer power is not sufficient, the treatment cycle is extended; and when transformer power is more than it is required, capital expenditure and power overconsumption increase and the ladle lining lifetime decreases [4, 5]. The analysis of Figure 1 shows that the increase in transformer power leads to an increase in the heating rate. However, the same heating rate can be obtained at various specific active power and, consequently, different power consumption (Figure 2) [6].
Figure 1. The dependence of the steel heating rate on active power supplied from the transformer.

Figure 2. The dependence of the steel temperature increase (heating rate) on the power consumption.

At the same power consumption, a temperature increase is different, since the efficiency of the unit, in addition to the heating rate, is determined by the heating efficiency or energy utilization factor [7, 8]. The dependence of the installed capacity of transformers on the ladle furnace on the weight of the processed steel shows a significant variation in values (Figure 3). By approximating the data by power dependence, we get a rather reliable result ($R^2 = 0.8$), but it is unlikely to accurately calculate the required transformer power for specific technological tasks. Therefore, suppliers equip the facilities with transformers with an overrated installed capacity, which is partially not used.

At the same time, power supplied to the ladle furnace is limited to the lining wear rate, and excessively supplied power inevitably leads to an increase in the wear rate of refractories in the slag belt zone and in “hot spots” of the cover. The so-called “hot spots” are associated with overheating of refractories in the immediate vicinity of the arc, which increases the consumption of refractory materials and leads to damages on an inner surface of the ladle. According to the data provided by Danieli company, maximum allowable specific power of the arc should be about 1.8–2.2 MW/m² of the liquid metal surface.

The most important technical and economic indicator of the ladle furnace operation is thermal efficiency of heating the heat. The value of efficiency is determined by both design features of the unit and the secondary treatment technology. Statistical processing of the available data [9] shows a significant variation in values, and for estimated calculations with sufficiently high confidence ($R^2 = 0.89$), the power dependence shown in Figure 4 can be used only for small capacity ladles.

Thus, these data can be used only for reference, and for the conditions under study we should calculate the relevant heat balance of the unit. The heat radiated from the furnace melting volume is dissipated through the lining of the roof, walls and bottom, escapes with cooling water and gases, and it is also radiated through the charging doors, etc.
Inert gas purging of steel in the ladle furnace, comparing favourably with other secondary treatment methods due to relatively low costs, allows successfully solving such tasks as reducing the heterogeneity of steel in its temperature and chemical composition, improving the conditions for removing non-metallic inclusions, and partially degassing the melt [9]. Heat loss with waste gases is one of the expenditure items of the heat balance. It is usually assumed in calculations that gas temperature has the temperature of the melt, when leaving the ladle furnace.

When calculating the heat balance of the ladle furnace, it is difficult to estimate the heat loss through the ladle lining, as well as its accumulation of heat during processing, although this is necessary for an accurate prediction of steel temperature changes. Therefore, this balance item is determined with a known inaccuracy, although it amounts to about one-third of the total heat loss of the furnace on average [10–12].

Heat transfer in the ladle furnace is determined by the conditions of electric arc burning. The immersion depth of the arc, depending on slag thickness, influences the efficiency of heat exchange between electric arcs and the melt and, consequently, the power consumption of the arc device of the unit. Paper [13] describes the dependence of slag thickness in the ladle on the specific energy consumption (Figure 5).

![Figure 5. The influence of slag thickness in the ladle on the specific power consumption.](image)

The slag layer thickness should cover at least 2/3 of the arc length in those cases when steel is not desulfurized, but adjusted by temperature only. The calculations [5] show that if 10 mm of the arc is not covered by slag, electric power losses amount to 2–3% of supplied power.

To determine the heat loss with cooling water, we should know input and output water temperatures at the cover of the ladle furnace, as well as the water flow rate [14]. The ladle furnace is equipped with temperature sensors that determine the water temperature discharged from each circuit and measure the water temperature supplied to the cover. Measurements carried out on the ladle furnace of the basic oxygen furnace shop at PJSC Magnitogorsk Iron and Steel Works (MMK) show that when the heating stage is turned on, the water temperature in the cover at a flow rate of 245 m$^3$/h increases in proportion to the heating time:

$$t_i = 0.015 \cdot \tau + 37.09,$$

where $t_i$ is water temperature at the outlet of the cover, °C; and $\tau$ is heating time, s.

Heat for heating cooling water in the ladle cover is calculated as follows:

$$Q_w = \begin{cases} P \cdot c_w \cdot (t_{01} - t_2) \cdot Q_k = 0 & \\ P \cdot c_w \cdot \int_{t_1}^{t_2} (0.015 \cdot \tau + 37.09 - t_2) \, dt, Q_k \to 0 & \\ \end{cases}$$

where $P$ is water consumption for the cover, m$^3$/s; $c_w$ is heat capacity of water at actual temperature, J/kg·°C; $t_{01}$ is water output temperature at the cover, when there is no heating, $t_{01} = 37$ °C; $t_2$ is water
input temperature at the cover, \( t_2 = 30 \, ^\circ C \); \( t_0 \) is the duration of the period without heating, \( s \); \( t_1, t_2 \) is end and starting time of heating, respectively, \( s \); \( \tau \) is current heating time, \( s \).

According to the data obtained as a result of the research, the heat loss with cooling water during heating can be 12–18% of energy supplied to heating.

2. Mathematical description
The system of circulating water supply, which allows fixing water consumption and temperature, has certain inertia. Accounting for heat losses with water over the entire treatment period on the ladle furnace may give an idea of a total level of such losses; however, when preparing operational balances, for example, for heating operations that last 5–7 minutes, may also give an error in the calculations [15].

Heating in the ladle furnace is a sequence of operations, each of them differs in the special features of the processes performed (heating, desulfurization, alloying) and their combination [16, 17]. The calculation of the heat balance at every stage is associated with a certain error, which influences the estimated average mass temperature of the melt by the end of the stage. When temperature is measured selectively, a true value of molten steel temperature at the beginning of the operation remains unknown and can only be estimated by calculation. Accuracy of the calculations was corrected by comparing the predicted calculated and measured values of temperature during processing and, as a result, according to temperature of the ladle transferred to the downstream operations [18].

To predict accurately the temperature change of steel during processing in the ladle furnace, it is necessary to calculate the heat balance items of the unit, when many of these items cannot be correctly estimated. For example, we cannot calculate accurately the heat loss through the ladle lining and the accumulation of heat by the lining during processing. To eliminate temperature gradients along the molten steel depth, the melt is mixed with argon supplied through porous plugs in the ladle bottom. Efficiency of blowing depends not only on the amount of supplied gas, but also on the condition of the plugs, slag on the steel surface and its physical state [19, 20].

As part of the study, we developed a software product adaptable to the conditions of a specific ladle furnace based on the classical equations of heat and mass transfer and a multivariate analysis of the database of heat reports for the unit over a long period. First, we analysed the database of 20,000 heat reports taken from the ladle furnace in the basic oxygen furnace shop at PJSC MMK to evaluate the influence of these factors on the processes of thermodynamics, heat and mass transfer and kinetics, and to integrate the analysis results in the form of correction factors into separate program blocks.

The program allows you to calculate the heat balance of the ladle furnace for a short period, the average mass temperature of the melt, the energy characteristics of heating and processing by entering various initial data. The model is executed in MATLAB with the Simulink software module.

As an example of organizing individual calculation blocks, we describe the block “Heat input from oxidation of electrodes” (Figure 6). The block calculates heat input from oxidation of electrodes during a total heating. During the combustion of 1 kg of graphite, 33520 kJ of heat is released, and the electrode consumption is 0.008 kg/kW·h of electric arc spent on burning. During the operation of the electric arc facility, the electrodes are oxidized with heat input coefficient \( Q_c = 0.074 \cdot Q \).

The heat input at every point of time is calculated according to this equation depending on the electrical power of the unit related to the transformer tap used during heating. Figure 6 shows the trend in heat flux at different taps (columns). As a result of the calculation, the window “Heat input from oxidation of electrodes” contains the total amount of heat for this item for a total period of treatment.

By using this program, we can evaluate the influence of melt heating efficiency at different stages of technological operations (Figure 7) in the ladle furnace and give recommendations for improving the heating technology.
Figure 6. Block “Heat input from oxidation of electrodes”.

Figure 7. Block “Heating steel”.

Thus, the mathematical model of the power supply system of the ladle furnace simulated the system operation at a level close enough to the actual behaviour studied in field tests. A criterion for the model accuracy was considered to be an insignificant error (most often the root mean square one) of the simulation results. At the model adjustment stage, the heat balance residual error was attributed to electrical losses. Model adequacy was proved by conducting control heats (10 heats of steel grade 09G2S) on the ladle furnace in the basic oxygen furnace shop of PJSC MMK. Inaccuracy in estimating the current temperature of the melt did not exceed 5 °C.

Studies on the database for the ladle furnace of PJSC MMK using the created model of heat balance allowed us to estimate a range of changes in heat loss items (Table 1).

Table 1. Ranges of change in heat loss items on the ladle furnace during a melting process (melting steel 09G2S, ID 19135).

| Heat loss items               | Range of changes (%) |
|------------------------------|----------------------|
| Outgoing gases               | 3-15                 |
| Water cooling the cover      | 15-45                |
| Slag induction               | 8-10                 |
| Adding alloying elements     | 0.5-1                |
| Electrical loss              | 10-20                |

3. Conclusion

Thus, the conducted studies on the mathematical model showed that maximum energy loss in the ladle furnace were attributed to losses with cooling water and in the electrical circuit. It should be noted that electrical losses are total energy losses of the electric arc, conditionally including radiation losses of a part of the arc uncovered by slag. By managing these flows, we create conditions for increasing heating efficiency. The calculations showed that a decrease in these losses is observed during prolonged heating (about 8–12 minutes) with a sufficient amount of slag. This mode provides a reduction in heat loss by 4–5%. By selecting options of changes in a sequence of stages and their duration, the proposed mathematical model makes it possible to apply a new technology to process molten steel in the ladle furnace characterized by lower power consumption.

References

[1] Agapitov E B, Nikolaev A A and Lemeshko M A 2018 Complex research of energy efficiency of electric arc furnace ladle installations International Multi-Conference on Industrial Engineering and Modern Technologies 8602500
[2] Agapitov E B, Kornilov G P, Khramshin T R, Erofeev M M and Nikolaev A A 2006 Thermal and electrical control of the ladle furnace Electrometallurgy 6 11–16
[3] Dyudkin D A, Bat S Yu, Greenberg S E and Marintsev S N 2003 Steel production on the ladle furnace (Donetsk: South-East, Ltd) p 300
[4] Kramarov A D and Sokolov A N 1976 Electrometallurgy of steel and ferroalloys (Moscow: Metallurgy) p 440
[5] Erofeev M M and Agapitov E B 2009 Mathematical simulation of nonstationary mixing of steel in a ladle furnace Russian Metallurgy (Metally) 7 571–575
[6] Steinberg L S, Goldberg L A, Kuzina V I, Vladimirov V A and Chaykin B S 1995 The software package for calculating the parameters of heat and mass transfer processes of after-treatment metal Steel 11 14–17
[7] Kats Ya L, Sinelnikov V A and Brodov A A 2004 Ladle furnaces for increasing the efficiency of electric steel melting Proceedings of the 8th Congress of Steelmakers 18–24
[8] Nikolsky L E, Smolyarenko V D and Kuznetsov L N 1981 Thermal work of electric arc furnaces (Moscow: Metallurgy) p 320
[9] Beitsun S V, Zhadanov A V, Mikhailovskiy N V and Shatalyuk S V 2004 Prediction of heat losses through the lining of the ladle during out-of-furnace processing of steel (Zaporozhye: Metallurgy collection of scientific papers) p 124
[10] Volkova Ye N, Bakhman S M and Sheller P R 2006 The influence of various lining materials on the thermal state of the after-treatment steel ladle Metallurgy and mining industry 7 314–320
[11] Kharlamov D A and Merker E E 2004 Development of a control algorithm for slag mode of out-of-furnace steel processing Energy Saving and Energy Efficient Technologies. Collection of reports of the All-Russian Scientific and Technical Conference 2 238–241
[12] Vikhlevshchuk V A, Kharakhulakh V S and Brodsky S S 2000 Ladle steel finishing (Dnepropetrovsk: System technologies) p 190
[13] Agapitov E B, Bigeev V A and Erofeev M M 2007 The results of the treatment of the steel melt on the ladle furnace with hollow electrodes Vestnik of Nosov Magnitogorsk State Technical University 1(17) 36–38
[14] Yakimov I A and Gasiyarova O A 2018 The energy-efficient control of the electrical regime of high-power electric arc furnaces: the case of EAF-180 MMK, PISC International Conference on Industrial Engineering, Applications and Manufacturing 1–5
[15] Agapitov E B 2011 Energy saving at jet-plasma bucket processing of steel melt Vestnik of Nosov Magnitogorsk State Technical University 4(36) 88–90
[16] Agapitov E B, Bigeev V A and Lemeshko M A 2011 Assessment of the effect of indistinctly controlled parameters on desulfurization in a ladle furnace Electrometallurgy 11 7–9
[17] Agapitov E B, Lemeshko M A and Sokolova M S Prospects for the use of hollow electrodes for deep desulfurization of steel in the ladle furnace Materials Science Forum 989 474–479
[18] Kartavtsev S V, Nikolaev A A, Neshporenko E G, Demin Yu K and Matveev S V 2016 Analysis of its own energy independent electric steelmaking process Proceedings of the 2016 IEEE North West Russia Section Young Researchers in Electrical and Electronic Engineering Conference 587–589
[19] Nikolaev A A, Tulupov P G and Antropova L I 2018 Heating stage diagnostics of the electric arc furnace based on the data about harmonic composition of the arc voltage Proceedings of the 2018 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering 742–747
[20] Khramshin V R, Evdokimov S A, Nikolaev A A and Karandaev A S 2015 Monitoring technical state of the Smart-Grid technology introduction within the industrial electric networks Proceedings of the 2015 IEEE North West Russia Section Young Researchers in Electrical and Electronic Engineering Conference 214–220