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Maxim HROMCHENKOV, Kyrylo KRASNIKOV
Dniprovksyi state technical university

STUDY ON THE BASIS OF COMPUTER MODEL OF STEEL HEATING PROCESS IN ORDER TO REDUCE RESOURCE COSTS

Steel is one of the most important materials in the modern world, used in various industries and construction. Steel production starts with heating steel melt in steel ladles, the equipment used in the steel industry to produce various types of steel. The ladle plays a key role in this process, as it is the place where the steel melt is heated. The search for rational technological layouts that ensure the economical use of material and energy resources in the manufacture of high-quality steel products is an urgent scientific and technical challenge facing the engineering staff of steelmaking and high-quality competitive steel products. Random increases and decreases in steel temperature can lead to deterioration in steel quality, accelerated erosion of refractory materials, and increased energy consumption. Steel heat losses depend on the ladle's thermal state, thermal and physical properties of the steel, and slag. The thermal state and thermal properties of molten steel and slag need to be quantified to better control the production process, the final steel composition, and the desired pouring temperature.

The experimental results, their analysis and systematization are presented. It is concluded that the most suitable materials for the melt heating process are ladles with the smallest geometric parameters together with RESISTAL B80 lining. In turn, the largest ladle during the experiments produces in most cases the highest resource costs with a steel casing – 498-1972 UAH and 0.18-0.74 MJ. In some results, comparing the steel casing with RESISTAL B80, the resource costs make up a slight difference – 3-7 UAH. and 0.001-0.003 MJ, and in others – 24-704 UAH and 0.009-0.266 MJ. At the same time, the bucket with medium geometric dimensions shows average indicators of resource costs – 423-1255 UAH and 0.16-0.47 MJ.

Software for modeling an industrial process has been developed that allows conducting numerical experiments for a particular steel melt with different input parameters to determine their impact on resource consumption. Saving the results of the experiments, it is possible to analyze the impact of input parameters on a particular melt and make the right decisions for further experiments.

Keywords: computational fluid dynamics, melt, cost reduction, steel ladle.

Максим ХРОМЧЕНКОВ, Кирило КРАСНІКОВ
Дніпровський державний технічний університет

ДОСЛІДЖЕННЯ НА ОСНОВІ КОМП'ЮТЕРНОЇ МОДЕЛІ ПРОЦЕСУ НАГРІВАННЯ СТАЛІ З МЕТОЮ ЗМЕНШЕННЯ ВИТРАТ РЕСУРСІВ

Сталь – один з найважливіших матеріалів у сучасному світі, який використовується в різних галузях промисловості та будівництві. Виробництво сталі починається з нагрівання металевого розплаву в сталерозливних ковшах – обладнанні, що використовується в металургійній промисловості для виробництва різних видів сталі. Ковш відіграє ключову роль у цьому процесі, оскільки саме в ньому відбувається нагрівання металевого розплаву. Пошук раціональних технологічних схем, що забезпечують економне використання матеріальних і енергетичних ресурсів при виробництві високоякісної металопродукції, є актуальним науково-технічним завданням, що стоїть перед інженерно-технічним персоналом сталеплавильного виробництва і якісної конкурентоспроможної металопродукції. Випадкові підвищення і зниження температури сталі можуть призвести до погіршення якості сталі, прискореної ерозії вогнетривких матеріалів і підвищених енерговитрат. Теплові втрати сталі залежать від теплового стану ковша, теплофізичних властивостей металевого розплаву та шлаку. Тепловий стан і теплофізичні властивості розплавленої сталі та шлаку необхідно визначати кількісно, щоб краще контролювати виробничий процес, кінцевий склад розплаву і бажану температуру розливання.

Представлено результати експериментів, їх аналіз та систематизація. Зроблено висновок, що найбільш придатними матеріалами для процесу нагріву розплаву є ковші з найменшими геометричними параметрами в поєднанні з футеровкою RESISTAL B80. У свою чергу, найбільший ківш під час експериментів дає в більшості випадків найбільші ресурсні витрати зі сталевою оболонкою - 498-1972 грн і 0,18-0,74 МДж. В одних результатах, порівнюючи сталевий кожух з RESISTAL B80, ресурсні витрати складають незначну різницю - 3-7 грн. і 0,001-0,003 МДж, а в інших - 24-704 грн. і 0,009-0,266 МДж. При цьому ківш із середніми геометричними розмірами демонструє середні показники ресурсних витрат - 423-1255 грн та 0,16-0,47 МДж.

Розроблено програмне забезпечення для моделювання промислового процесу, що дозволяє проводити чисельні експерименти для конкретної плавки сталі з різними вхідними параметрами для визначення їх впливу на витрати ресурсів. Зберігаючи результати експериментів, можна аналізувати вплив вхідних параметрів на конкретну плавку і приймати правильні рішення для подальших експериментів.

Ключові слова: комп'ютерне моделювання, розплав, зменшення витрат, сталерозливний ковш

Introduction

Reducing resource costs at steelmaking companies is a crucial task. Production efficiency and cost management play a key role in ensuring the competitiveness of enterprises engaged in industrial processes. To achieve these goals, it is important to analyze and optimize various aspects of production processes, such as temperature control, heat loss, and energy management. These measures can improve product quality and help reduce resource costs.

Related works

Most of the solutions found in the literature refer to three stages of the steel production process: melting in arc furnaces [1], refining [2] and continuous casting [3]. On the other hand, the analysis of heat losses in ladles is mainly considered from the point of view of their design.

Such a model was presented in work [4], where the optimal parameters of bucket lining were determined with minimal energy consumption. The model describes the heat exchange of molten steel during ladle transportation between stations. The ladle of the refining unit can determine the temperature of the molten steel under various production parameters, such as the steel grade and the weight of the molten steel. Predicting the temperature at which the ladle arrives at the continuous steel casting station (CSST) is important to plan for overheating during casting and to ensure sufficient time for the ladle to leave the steel casting station at the steel plant.

One of the main approaches used to calculate the required amount of electricity consumed by industrial equipment of metallurgical enterprises is the approach based on the use of regression dependencies of electricity consumption on important factors of the production process. The solution to the problem of electricity consumption based on the forecasting of electricity based on multivariate regression and correlation analyses was also carried out in [5-6].

In [7] emphasizes that the most energy-intensive steelmaking process using electric arc furnaces (EAFs) is subject to automation limitations and decisions related to furnace loading volume, while operators typically make decisions about electrode placement time. The authors proposed a recommendation system based on an economically optimal operating model to support the operator's real-time decision-making for an economically optimal process.

Purpose

A mathematical modeling method was used to predict the thermal state of the liquid metal in the ladle. The calculations took into account the geometric parameters of the steel ladle, thermal properties of the steel melt, slag and lining. For the purpose of this study, the ladle is an open container that receives the molten steel and some slag. In the ladle, 3 graphite electrodes are placed, which are designed to supply electric current to the melt to heat it. The total power of these electrodes is 25000000 W. There are assumptions for mathematical model:

1) View of a steel ladle in the form of a cylinder (Fig. 1).
2) Geometric properties of a steel ladle, which are presented in table 1.
3) Thermal properties of steel melt, slag and lining, which are presented in tables 2-4.

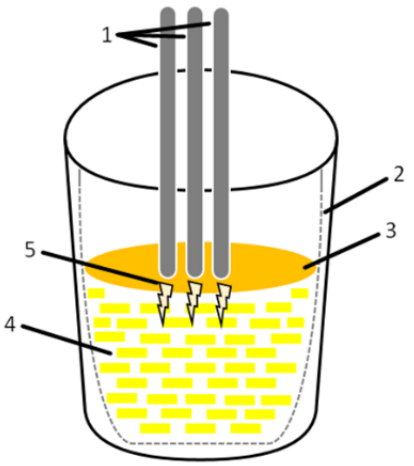

Fig.1. Simplified scheme of a steel ladle
1 - graphite electrodes, 2 - lining, 3 - slag, 4 - liquid metal (melt), 5 - electric current

Table 1

Geometric dimensions of the steel ladle

Ladle number, №	Capacity, t	Height, mm	Average diameter, mm
1	50	2800	2480
2	100	3450	3175
3	250	4350	3885
4	480	5660	4977

Table 2

Thermal properties of melts

Steel melt	Thermal conductivity, $W/(m \cdot K)$	Heat capacity, $Joule/(kg \cdot K)$	Density, kg/m^3	Temperature, K
Iron	50	85	7000	1815,5
Structural steel	30	500	7000	1998,15
Carbon steel	35	550	7500	1723,15
High strength cast iron	40	650	7900	1673,15
Gray cast iron	25	500	6950	1533,15
White cast iron	40	550	7100	1482,15

Table 3

Thermal properties of slag

Material	Thermal conductivity, $W/(m \cdot K)$	Heat capacity, $Joule/(kg \cdot K)$	Density, kg/m^3	Temperature, K
Slag	1,8	1	2675	1473,15

Table 4

Thermal properties of lining

Lining	Thermal conductivity, $W/(m \cdot K)$	Heat capacity, $Joule/(kg \cdot K)$	Density, kg/m^3	Temperature, K
RESISTAL B80	1,8	1212	7000	1815,5
	1,8	1342	2750	1873, 15
	2	1070	2200	673, 15
Steel casing	42	430	7730	673, 15

The heat conduction equation was used to model the process of heating the steel melt and the change in the temperature of the materials over time:

$$\frac{du}{dt} = \frac{k}{cp}\frac{d^2u}{dx^2} - \frac{\mu}{cp}(u^4 - v^4) \quad (1)$$

where $\frac{du}{dt}$ – rate of change of melt temperature over time; k – coefficient of thermal conductivity of the melt; cp – specific heat capacity of the melt; d^2x/dx^2 – dispersion of the melt temperature along the x coordinate; μ – heat transfer coefficient, which characterizes the amount of heat radiated from a unit of material surface per unit of time; u^4 – fourth degree of the melt temperature function; v^4 – the fourth degree function of ambient temperature.

Emissivity is the degree of an object's ability to absorb and emit energy, i.e. how well the body emits and absorbs energy. In this study, we chose this coefficient of 0.3, and its consideration gives a more accurate result and optimization of resource costs.

The Stefen-Boltzmann constant (law, proportionality coefficient) associated with the blackness coefficient was also taken into account in the thermal process:

$$\sigma = 5{,}6 \cdot 10^{-8} \cdot \frac{Vatt}{m^2 \cdot T^4} \quad (2)$$

To calculate the flows between two points in the system (upstream and downstream), taking into account temperature differences, distance, and thermal conductivity, the Fourier's law (heat conduction) was used. Since the system used layers of air, slag, molten steel, and lining, this law was used to calculate the heat flow between adjacent layers:

$$q = -k\nabla T \quad (3)$$

where q – heat flux; k – thermal conductivity coefficient; ∇T – temperature gradient (temperature difference in space).

In addition, the volume of steel melt in the ladle (75%) was taken into account for all experiments. This made it possible to take into account the volume of liquid steel to heat it, which affected the thermal state and temperature gradient. The area of the bottom and side walls of the ladle was also calculated. In this case, the heat flow calculations are determined in relation to these geometric parameters.

Based on this mathematical model, software was developed to perform numerical studies and analyze the melt heating process with various parameters and their combinations. The main task of this software is to analyze and search for parameters that meet the requirements of the industrial process to reduce resource consumption.

The program has a user-friendly interface through which the user explores the industrial process to find and analyze parameters for certain conditions in order to reduce resource costs. To start the study, the user must select a specific ladle, metal melt, slag and enter such input parameters as: process duration, initial temperature of melt, slag and lining, temperature above slag, room temperature, temperature of electrodes on and off.

After the experiment, the user can save it to the database for further analysis and compare it with others to find the optimal melt heating option. The results obtained can be useful and used for further research on this topic.

During the experiment, the graph displays changes in the temperature of the materials in real time, which makes it possible to study and analyze thermal processes and their dynamics during the experiment.

The C# programming language was chosen to create the software, SQL Server was chosen to store and manage data, and the SQL Server Management Studio (SSMS) environment was chosen as the interface for managing and creating queries. A logical model of the data base is presented in figure 2.

To display the modeling results, we used the chart component, a control for building various types of graphs and charts.

The graphical user interface was developed using Windows Forms technology, which is part of the Microsoft .NET Framework platform, which has a large set of controls, convenient and wide functionality that allows you to quickly and easily create an attractive and functional user interface.

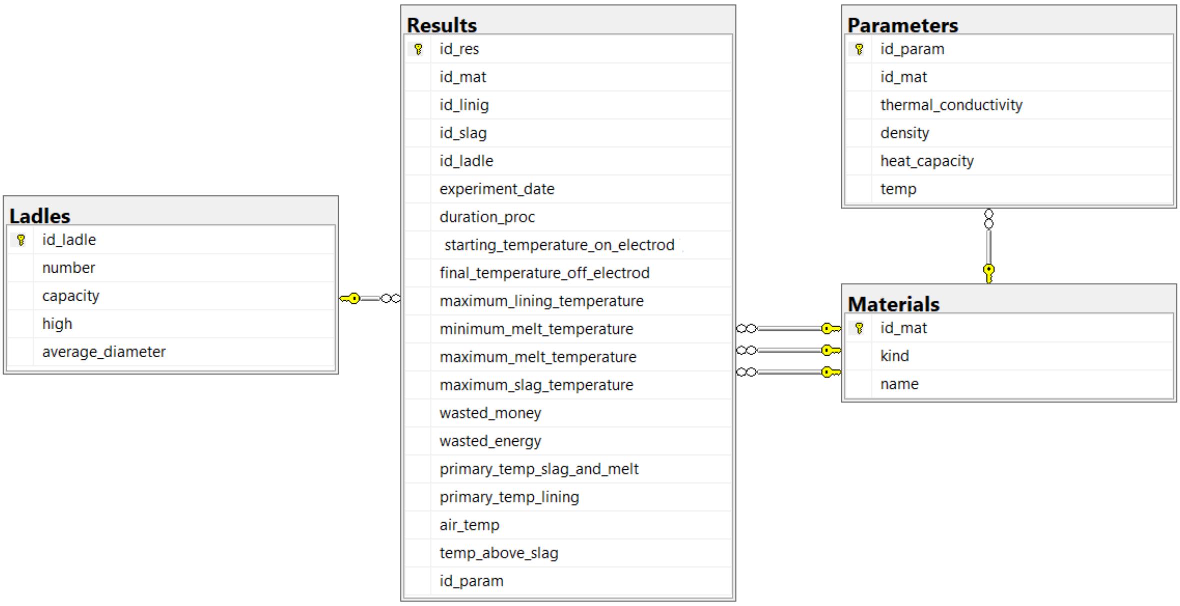

Fig. 2. Logical model of the database

Results

To conduct experiments on the process of heating the steel melt, the heat conduction equation was chosen as the basis for the experiments. During the experiments, the data given in the tables 1-4 and the input data such as: process duration, initial temperature of melt, slag and lining, temperature above slag, room temperature, temperature of electrodes on and off. During the experiments, 100 results were obtained. The duration of each experiment was 10 minutes

Based on the results of the iron melt, we can conclude that the optimal parameters for its heating in terms of resource costs are the following: ladle № 2, RESISTAL B80 lining, electrode exclusion temperature – 1815 and 1830, K; initial melt and slag temperature – 1820, K. In the course of this, 0.16 MJ and 423 UAH were spent. The result of this experiment is shown in figure 2.

The most costly result of heating an iron melt, the graph of which is shown in figure 3, is the following experiment with the following parameters: ladle № 4, steel casing, electrode shutdown temperature – 1812 and 1820, K; initial melt and slag temperature – 1815, K As a result, 0.232 MJ and 612 UAH were spent. The result of this experiment is shown in figure 3.

These results show that in most cases, the materials that have a more costly impact on resource costs are bucket No. 4, which has the highest geometric properties throughout the study, together with the steel casing. In turn, buckets No. 1 and 2, which have the smallest dimensions and are lined with RESISTAL B80, show more favorable results.

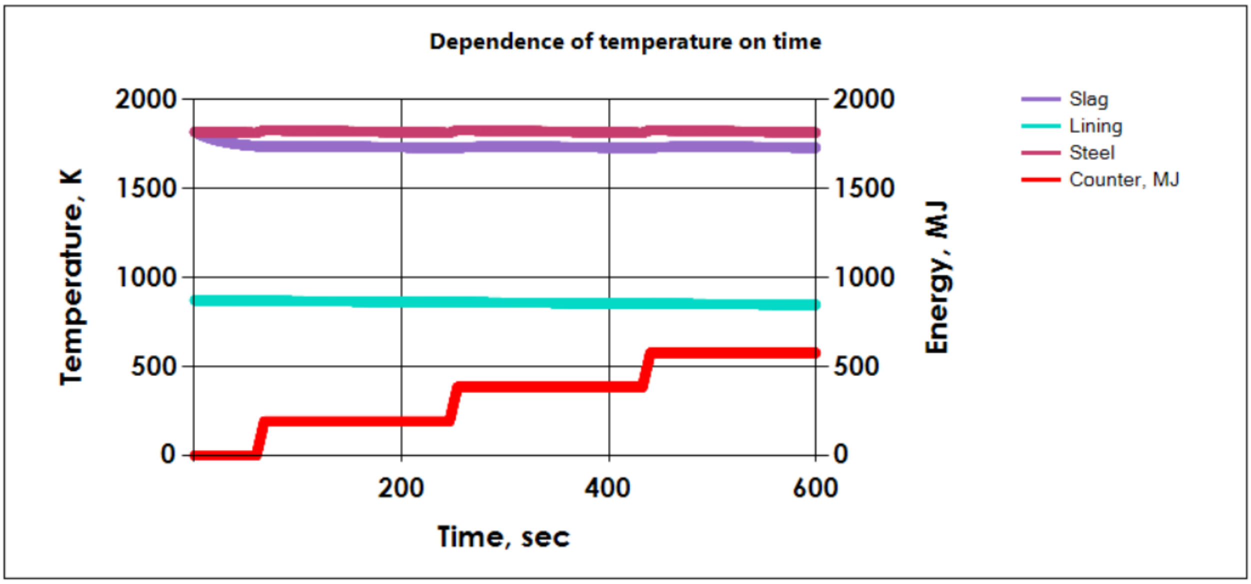

Fig. 3. Chart of experiment with the most energy-efficient consumption of resources for melting iron

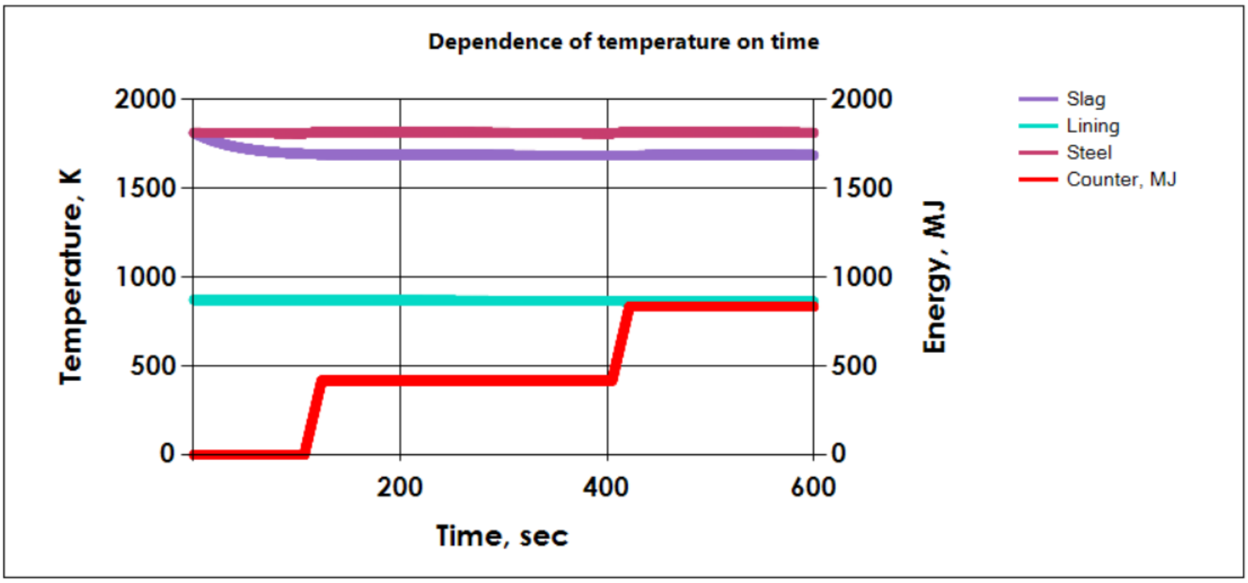

Fig. 4. Chart of the experiment with the largest resource costs for melting iron

Conclusions

The experimental results, their analysis and systematization are presented. It is concluded that the most suitable materials for the melt heating process are ladles with the smallest geometric parameters together with RESISTAL B80 lining. In turn, the largest ladle during the experiments produces in most cases the highest resource costs with a steel casing – 498-1972 UAH and 0.18-0.74 MJ. In some results, comparing the steel casing with RESISTAL B80, the resource costs make up a slight difference – 3-7 UAH. and 0.001-0.003 MJ, and in others – 24-704 UAH and 0.009-0.266 MJ. At the same time, the bucket with medium geometric dimensions shows average indicators of resource costs – 423-1255 UAH and 0.16-0.47 MJ.

Software for modeling an industrial process has been developed that allows conducting numerical experiments for a particular steel melt with different input parameters to determine their impact on resource consumption. Saving the results of the experiments, it is possible to analyze the impact of input parameters on a particular melt and make the right decisions for further experiments.

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Kyrylo Krasnikov **Кирило Красніков**	PhD, Associate Professor of Systems Software Department, Dniprovskyi State Technical University, Kamianske, Ukraine, e-mail: kir_kras@ukr.net orcid.org/0000-0002-4241-0572, Scopus Author ID 57205319971, ResearcherID: Q-8835-2017	кандидат технічних наук, доцент кафедри програмного забезпечення систем, Дніпровський державний технічний університет, Кам’янське, Україна
Maxim Hromchenkov **Максим Хромченков**	Master student of Systems Software Department, Dniprovskyi State Technical University, Kamianske, Ukraine, e-mail: maxhom1000@gmail.com orcid.org/0009-0008-9838-5215	магістрант кафедри програмного забезпечення систем, Дніпровський державний технічний університет, Кам’янське, Україна