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Situational model of technological operations for secondary metallurgy

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ABSTRACT

Purpose: The aim of this study was development of a computer situational model of heat and power processes and transport operations for secondary steelmaking (SSM) to evaluate the effectiveness of the proposed SSM energy regimes and minimization the consumption of energy resources.

Design/methodology/approach: For the solution of the tasks were used next methods: analytical and statistical methods of mathematical modeling; method of dynamic programming for the development of technological recommendations for energy modes on LF; Harel state charts to evaluate the effectiveness of the applied models.

Findings: In order to provide rational energy regimes for SSM, it is necessary to introduce a new controlled parameter - the optimum time to start heating the melt at the ladle furnace unit (LF), which is determined by solving the dynamic programming task. The melt heating start time must be selected in such a way as to ensure that all the necessary technological operations are performed during metal processing in the LF, taking into account schedule constraints, and that the heating of the metal must be carried out with the maximum energy efficiency.

Research limitations/implications: The main objective of the present study was to apply the mathematical modeling methods to ensure rational energy regimes of SSM.

Practical implications: The developed situational model of technological operations for SSM will allow finding reserves to increase the productivity and quality of the process, and to evaluate the effectiveness of new technological solutions.

Originality/value: To ensure an energy-efficient treatment of steel in LF, it is necessary: the time for starting the heating of the metal is chosen such that the energy efficiency of the LF, which depends on the thickness of the slag layer, is maximum at each stage; increase the power that is supplied to the heating of the melt by switching the voltage taps of the transformer as the thickness of the slag cover increases.

Keywords: Situational model, Secondary metallurgy, Heat energy models, Method of dynamic programming

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ANALYSIS AND MODELLING

1. Introduction

Metallurgical industry is one of the most energy consuming. In some causes, it is necessary to maintain the temperature of steel, in order to carry out a certain type of treatment. A significant input of energy sources is required to maintain the temperature, which depends upon duration of technological operations. Modern trends of metallurgical industry development require a minimization of energy consumption. One of the ways to cut down expenses associated with energy sources is to limit time of technological and handling operations. Development of the situational model of technological operations will allow solving such tasks in a more efficient manner.

The methodology of structural modelling was developed in the 50's-60's of the last century [1]. A language of logic circuits, which existed at that time, was used for a good description of structural links in the system, but its means were not sufficient for multidimensional transformations of the characteristics of material treated at production units.

The application of the finite automata theory [2-4] and its further development, so-called Harel state charts [5-9], which form the basis of up-to-date modelling software packages [10,11], allow to lift mentioned restrictions. The possibilities of modern computer modelling are clearly demonstrated in works [12,13].

2. Development of situational model

Secondary steelmaking procedure is shown in Figure 1. Where the following temperature parameters parameters are marked: meas.T_{tap}, meas.$T_{melt.0}$, meas.$T_{LF.start}$, meas.$T_{LF.1-2}$, meas.$T_{LF.fin}$, meas.$T_{VD.start}$, meas.$T_{VD.fin}$ – respectively, temperatures of the melt before tapping, in the ladle after tapping, at the beginning of LF treatment, during LF treatment, upon completion of LF treatment, at the beginning and end of vacuum degassing, which are measured with thermocouples; limits of $T_{VD.fin}$ – required range of steel temperature after vacuum degassing before casting; $T_{proc.start}$ is determined using the model melt temperature, which is required to calculate and to deliver information realise about steel treatment process on LF in accordance with the developed algorithm.

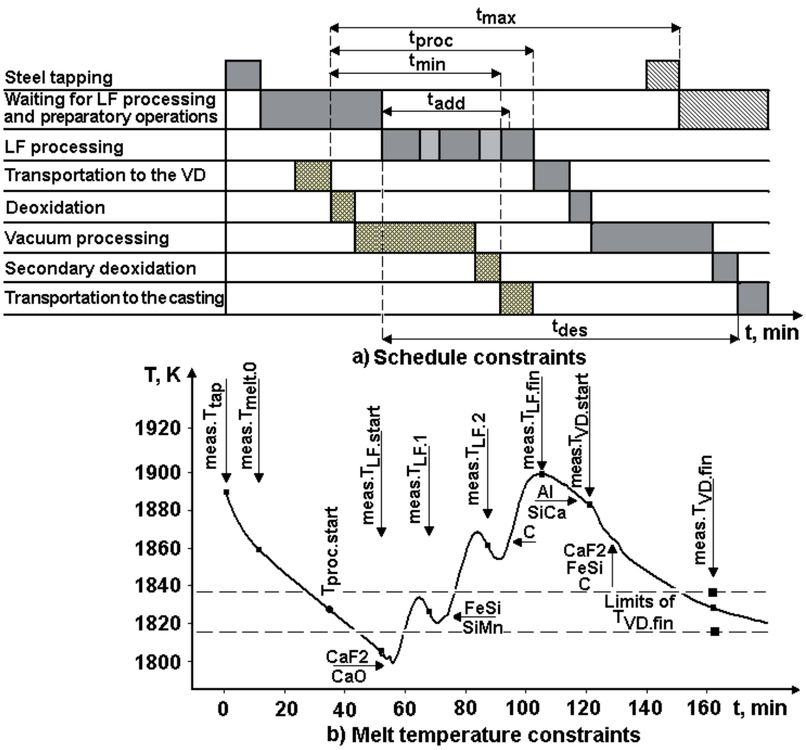

Fig. 1. Temperature-time diagram of the secondary metallurgy (explanation of the notations is given in the text)

When organizing the technological process, it is necessary to take into account the minimum possible time for secondary steelmaking (t_{min}), at which it is possible to perform vacuum degassing of the ladle, as well as consider the maximum allowed time of secondary steelmaking (t_{max}), determined by the frequency of tapping of subsequent heats from the steelmaking units.

The situational model of Secondary Metallurgy Area consists of the following main elements (Fig. 2):

1. Diagram of situational modelling "Technological operations", in which the sequence of technological operations at Secondary Metallurgy Area is visually displayed;
2. "Initial data" subsystem, which determines the time for technological operations at Secondary Metallurgy Area and values of such technological parameters as melt weight (W_{melt}), initial melt temperature in the ladle after tapping ($T_{melt.0}$), temperature of ladle lining inner surface before semi-finished product is tapped from the furnace ($T_{lin.0}$);
3. "Melt" subsystem, which includes models of thermal state of the melt in the ladles during technological operations at Secondary Metallurgy Area;
4. "Rational Energy Mode" subsystem, which is designed to provide information about steel treatment management in Ladle-Furnace in accordance with the developed algorithm;
5. Elements of the graphical user interface, with the help of which all the necessary technological parameters of the secondary steelmaking are introduced.

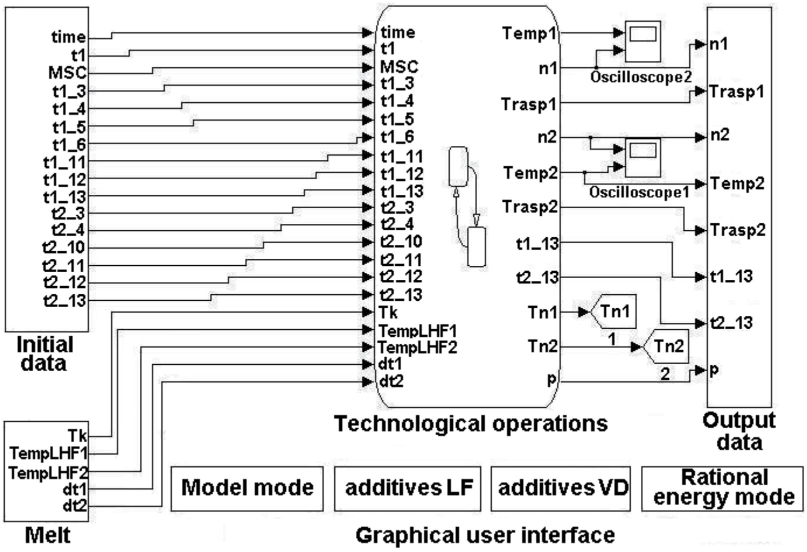

Fig. 2. General view of the situational model for secondary metallurgy steelmaking

The block of situational modelling "Technological operations" (Fig. 3) is organized as two parallel "chains of events" with the names "Ladle 1" and "Ladle 2", thus, corresponds to the technological operations made with the first and the second ladle. Input values of this block are times of technological operations for two ladles, as well as the values of optimal overheating of the melt over the liquidus line. Within each of the two parallel states are nested states that are connected by conditional transitions. These nested states specify the operation of the states "Ladle 1" and "Ladle 2". The time required for the technological operations performance at the Secondary Metallurgy Area, as well as the values of technological parameters (for example, M_{melt}, $T_{melt.0}$, $T_{lin.0}$) are determined by the model subsystem the "Initial Data".

In case if the model works according to «determine behaviour», the timing of technological operations, as well as M_{melt}, $T_{melt.0}$, $T_{lin.0}$, is specified through a specially designed graphical user interface connected with the described subsystem.

In order to ensure the model operation in the "stochastic behaviour" mode we used statistical information obtained by us while conducting industrial experiments, during which the time of performing technological operations was recorded, as well as the values of M_{melt}, $T_{melt.0}$, $T_{lin.0}$. It has been established that the duration of each technological operation is well described by generalized log-normal distribution laws, and technological parameters M_{melt}, $T_{melt.0}$, $T_{lin.0}$ are distributed according to the normal distribution law. Estimation of the adequacy of the selected distribution laws was verified by Pearson's chi-square test and $n\omega^2$ criteria [14].

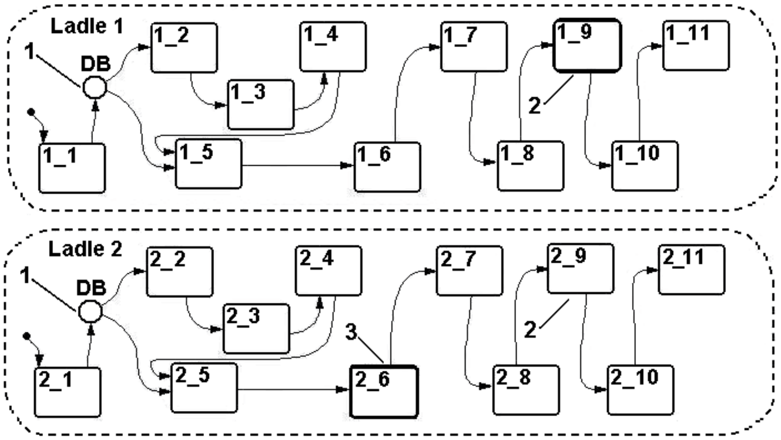

Fig. 3. General view of the situational modelling diagram "Technological operations": 1 – decision-making unit (provides alternative flow of the technological process), 2 – performed technological operation – vacuum degassing of the first ladle, 3 – performed technological operation – processing of the second ladle on the LF

The change in thermal state of the melt in the ladles during secondary metallurgy processes and the optimal overheating of the melt over the liquidus line for two ladles are described in the model subsystem "Melt".

Mathematical models describing the dynamics of the melt thermal state at the technological stages of secondary steelmaking were obtained and incorporated to the subsystem to solve these problems.

For example, in [15], based on the results of the heat-energy processes modeling in the ladle-furnace unit, we established that the the increase of molten steel temperature during LF heating without considering the introduction of slag-forming and alloying additives and deoxidizing agents may be well described with the following equation:

$$\Delta T_m = k_1 \cdot t_h, \tag{1}$$

where t_h is heating time and k_1 is the empirical factor determined from the formula:

$$k_1 = a_j \cdot H_{sl} + b_j \cdot M_m + c_j \cdot Q_{Ar} + d_j \cdot t_{tap} + e_j \cdot T_{LFstart.} + f_j \cdot T_{l.0} + g_j \,, \tag{2}$$

where H_{sl} is the thickness of covering slag, mm; M_m is the mass of the molten steel, t; Q_{Ar} is the argon specific flow rate, l/min·t; t_{tap} is the time past from the completion of the molten steel tapping into the ladle, min; a_j, b_j, c_j, d_j, e_j, f_j are the equation factors depending upon transformer tap.

The solution of the task for determining the rational power mode of the LF for the two melts is made in the subsystem "Rational Energy Mode", the output parameters of which are: the start time of the metal heating process and the sequence of voltage switching on the transformer taps.

The optimization task of the energy regime during LF process is formulated as follows: for a given time (t), with the minimum possible consumption of active electrical energy (E_{act}), transfer the required heat reserve to the melt for the subsequent technological operations. The goal function is defined by expression:

$$E_{акт} = \sqrt{3} \cdot \sum_{j=1}^{n} U_{2.j} \cdot I_{2.j} \cdot \cos\varphi_j \cdot t_{heat.j} \rightarrow \min, \tag{3}$$

where $t_{heat.j}$ – heating time on voltage step j, $U_{2.j}$, $I_{2.j}$ respectively represent secondary coil nominal voltages and currents of three-phase transformer with a tap j, $\cos\varphi_j$ – the factor of transformer power with a tap j.

The solution of the problem consists in determining the time of the beginning of the metal heating on the LF and the time sequence of switching the voltage taps of the transformer. When developing the algorithm, it is necessary to take into account the influence on the work of the LF of adjacent technological units of the secondary metallurgy section of steel - slag loading machine and vacuum degasser units, as well as steelmaking furnaces.

This ordains the schedule constraints for the duration of LF process (Fig. 1a):

$$t_{\min} \le t_{proc} \le t_{\max}; \quad t_{des.\min} \le t_{proc.LF}; \\ t_{add} + t_{assim} \le t_{heat} \tag{4}$$

where $t_{proc} = t_{proc.LF} + t_{ip}$ – time of secondary steelmaking, which includes melt processing on LF and its holding under insulation powder prior to heating; t_{min} – the minimum possible time for secondary treatment, after which it is possible to vacuum this ladle; t_{max} – the maximum possible time of secondary treatment, determined by the frequency of release of subsequent melts from steelmaking furnaces; $t_{proc.LF} = \sum_{j=1}^{n} t_{heat.j} + t_{stop}$ – duration of LF process which includes heating at voltage taps and technological stops; $t_{des.min}$ – time of secondary metallurgy, which ensures the desulphurization of steel; t_{add} – time of addition of the last portion of alloying, deoxidizing and slag-forming materials; t_{assim} – time of assimilation of additives.

Taking into account that the temperature of steel before casting should be in the range specified by technological requirements, which depends on the steel grade The heat balance equation is the main limitation of the energy economy task (Fig. 1b).

$$E_{melt} = \sum_{t_{proc}=1}^{n} \Delta E_{melt.t}, \quad (5)$$

where E_{melt} – energy which we need to input into melt during processing; $\Delta E_{melt.t}$ – energy increment of melt energy per each processing step, which occurred due to energy input during LF processing and heat losses because of heat transfer through ladle lining, radiation from melt and slag surface. The value E_{melt} was determined from expression:

$$E_{melt} = M_{melt} \cdot C_{melt} \cdot (T_{LF.fin} - T_{proc.start}) + E_{add}, \quad (6)$$

where E_{add} – energy costs associated with heating and melting chemical additives; $T_{LF.fin}$ – the temperature of the melt, at the excess of which the processing on the LF should stop; $T_{proc.start}$ – temperature at the initial step of solving the dynamic programming problem.

The main features of this task are:

- the time at which it is possible to determine the most favorable starting time for metal heating and the sequence of switching of the voltage stages, depends on the processing of the previous ladle;
- the moment of the beginning of the melt processing on the LF is determined by the time to which the heating of the metal must be completed, as well as by the random nature of the input parameters (M_{melt}, $T_{fut.0}$, $T_{melt.0}$);
- not the end point of the heating path (temperature) is set, but the range of permissible temperatures is set at the end of the next operation – vacuum degassing;
- the time period between the end of the LF processing and the beginning of the vacuum degassing is a random value.

Therefore we use dynamic programming method [16-20] and Bellman equation to solve this task [21].

In this case Bellman equation has next view [22]:

$$E_{act}(u) = \min\left[E_{act.n}(u_n) + f_{n+1}\left(E_{melt.n} - \Delta E_{melt.n}(u_n)\right)\right], \quad (7)$$

where $E_{act}(u)$ – active electrical energy expended during processing time; $\Delta E_{act.n}(u_n)$ – active electrical energy expended for *n* processing steps in process mode *u*; $f_{n+1}(E_{melt.n} - \Delta E_{melt.n}(u_n))$ – the minimum value of the objective function at the n + 1-st step, taking into account the processing mode at step n; $E_{melt.n}$ – the energy that must be reported to the melt at the time of the n processing step, $\Delta E_{melt.n}(u_n)$ – the energy transferred to the melt at step n.

The function f_{n+1} is related to the active energy by the following relation

$$f_{n+1}\left(E_{melt.n} - \Delta E_{melt.n}(u_n)\right) = (u=1) \cdot \Delta E_{act}(u=1) + \\ + \ldots + n(u=6) \cdot \Delta E_{act}(u=6) \quad (8)$$

where $n(u=1) \ldots n(u=6)$ – number of steps with modes $u = 1 \ldots 6$; $\Delta E_{act}(u=1) \ldots \Delta E_{act}(u=6)$ – active electric energy expended for the step of processing under modes $u = 1 \ldots 6$.

The number of steps with regimes $u = 1 \ldots 6$ was determined by solving the inequality

$$E_{melt.n} - \Delta E_{melt.n}(u_n) \geq n(u=0) \cdot \Delta E_{melt}(u=0) + \\ + \ldots + n(u=7) \cdot \Delta E_{melt}(u=7), \quad (9)$$

where $\Delta E_{melt}(u=0) \ldots \Delta E_{melt}(u=7)$ – increment of heat reserve per step of processing under modes $u = 0 \ldots 7$.

When solving the dynamic programming problem, the variability of the structure of possible modes:

$$\begin{rcases} \text{if} \quad u_{n-1} = 0 \quad \text{that} \quad u_n \in [0 \ldots 6], \quad u_n \in Z \\ \text{if} \quad u_{n-1} \neq 0 \quad \text{that} \quad u_n \in [1 \ldots 7], \quad u_n \in Z \end{rcases} \qquad (10)$$

The above listed systems are linked to the elements of the graphical user interface.

3. Modelling and analysis of results

To analyze the effectiveness of mathematical models considered real industry situations:

- the melt with a mass of 113.2 tons and an initial temperature of 1600°C is discharged into a ladle with $T_{lin.0} = 900$°C;
- 23 minutes after the steel tapping, due to the employment of LF unit, the metal mirror after the slag removal is finished is insulated with a special powder;
- after exposure under the insulating layer for 27 minutes, it became possible to solve the problem of optimizing the energy regime, taking into account that the deoxidization and vacuum treatment of this melting can begin not earlier than 56 minutes, i.e. $t_{proc} \geq 56$;
- The temperature after which it is necessary to finish the heating of the metal is $T_{LF.fin} = 1611$°C.

When solving the problem of dynamic programming, it was assumed that the flow of argon is known in advance, as well as the quantity, type and time of chemical additions.

With the treatment mode proposed by us, the heating of the metal is carried out without intermediate stops, and the start time for heating on the LF is chosen in such a way that the energy efficiency of the LF process, depending on the slag thickness, at each step of processing is maximal. The active electric power consumption was 17.2 MJ (4780 kWh). When processing metal under the operator's control, 20.6 MJ (5730 kWh) of active electrical energy was consumed – 20% more than in the first case (Fig. 4).

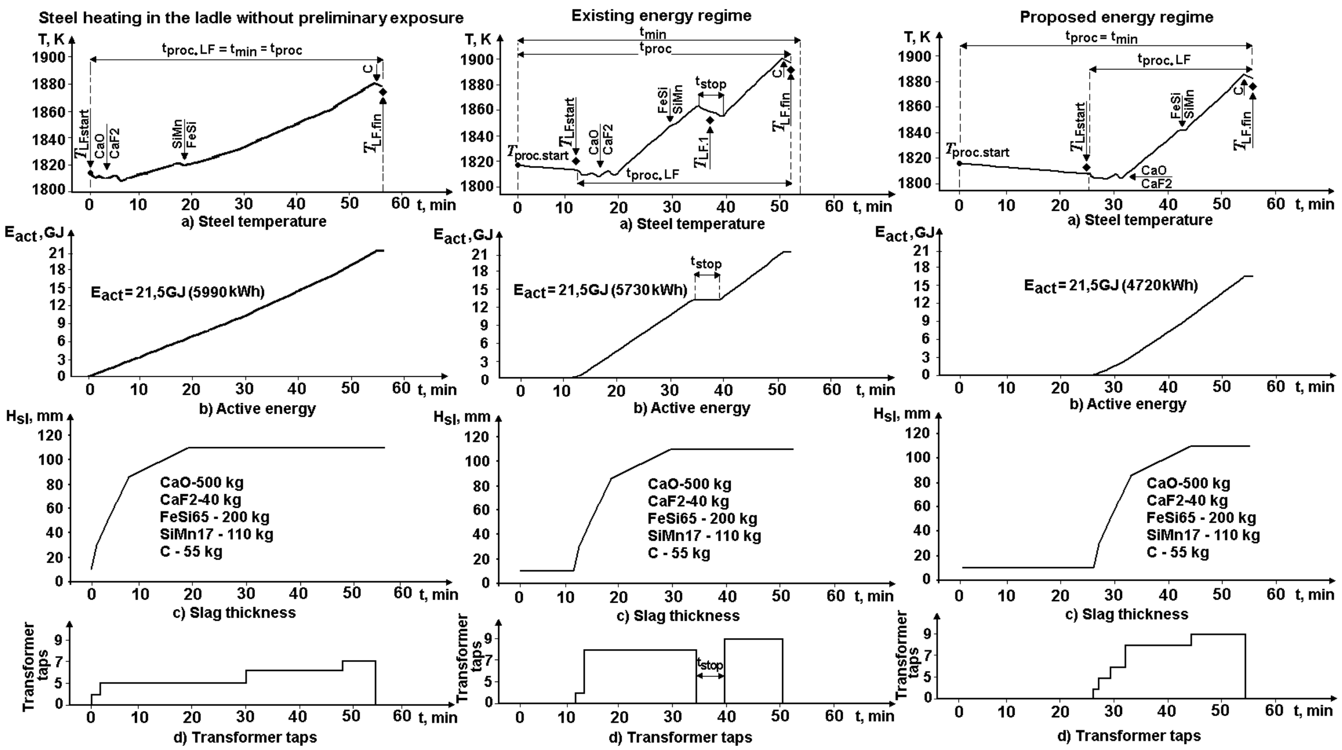

Fig. 4. Comparative results of energy regimes: existing, proposed, heating mode without preliminary exposure: a) steel temperature, b) active energy, c) thickness of slag cover, d) voltage stage

4. Conclusions

Using the method of dynamic programming, an algorithm for calculating the optimal energy regime at each stage of metal processing on the LF has been developed, which makes it possible to issue operational recommendations on heating control thereby:

- the time for starting the heating of the metal is chosen such that the energy efficiency of the LF, which depends on the thickness of the slag layer, is maximum at each stage;
- to increase the power that is supplied to the heating of the melt by switching the voltage taps of the transformer as the thickness of the slag cover increases.

The developed situational model of technological operations for Secondary steelmaking will allow finding reserves to increase the productivity and quality of the process, and to evaluate the effectiveness of new technological solutions.

The model can work in two modes of behaviour – "deterministic" and "stochastic". When working in the "deterministic" behaviour, the user independently sets the technological parameters for Secondary steelmaking.

In order to ensure the operation of the model according to the "stochastic" behaviour, statistical information obtained during industrial experiments was used, during which the time of performing technological operations, as well as the values of M_{melt}, $T_{melt.0}$, $T_{lin.0}$ were recorded. It is established that the duration of each technological operation is well described by generalized log-normal distribution laws, and technological parameters distributed according to the normal distribution law.

The method of situational modelling, which is described in this paper, might be widely applied for studies and optimization of technological systems.

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