

INDUSTRIAL APPLICATION OF REAL-TIME SIMULATION MODEL OF WALKING-BEAM REHEATING FURNACE

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Abstract

This paper presents industrial application of real-time simulation model for determination of temperature fields of steel billets in continuous reheating furnace, which was recently implemented in production process in steel industry. Simulation model is capable of simultaneous real-time calculation of temperature fields of all products charged in the furnace. Basic concepts of modeling heat exchange in gas-fired continuous furnaces are presented. The thermal radiation heat transfer in models is considered using the exact geometry of the furnace enclosure, including the geometry of billets inside the furnace. The heat conduction in the stock is calculated in three-dimensions by using finite-difference method. The algorithms of simulation model are optimized in terms of speed in order to achieve real-time operation. Validation procedure on the base of measurements on furnace during the normal production process is described. For real-time operation in the production process the simulation model needs additional modules which are used for its integration into information system of the plant. The organization of database system for storing the database results is presented. The graphical user interface was developed for simulation model in order to achieve user-friendly presentation of simulation model results.

Keywords: Real-time simulation, Continuous reheating furnace, Radiative heat transfer, Monte Carlo, View-factor.

Presenting Author's biography

Anton Jaklič is a researcher at the Institute of Metals and Technology (IMT) in Ljubljana Slovenia. He graduated in electrical engineering at the University of Ljubljana in 1994, he received M.Sc. in 1998 and PhD. in 2002. He has worked at IMT since 1994. He has been a Head of Heat engineering laboratory at IMT since 2005. His main research interests are simulations and data mining in steel industry.



1 Introduction

Continuous reheating furnaces in steel industry are used for heating the material to the temperature suitable for further thermo-mechanical processing i.e. rolling, forging etc. Available measuring methods in a high temperature furnace environment (1300°C) allow only measurements of stock surface in a few points during furnace operation. Most of measurements are available when the stock is already out from the furnace. The furnace operation is in most cases based on production tables tailored to the range of manufactured products [1]. These tables correspond to steady-state operation which is seldom achieved in the production process because of: change in steel grade, change in stock dimensions, different initial temperatures of stock and planned/unplanned stoppages. Monitoring of stock temperatures during the reheating process in the furnace is important for the furnace control and for the stability of further processes i.e. rolling.

In recent years, simulation models of reheating furnaces that can calculate the actual temperature distribution in the stock have been developed with increasing computational power. One-dimensional online temperature calculation of stock in the direction of thickness is presented in [2,3,4], models [3,4] are used also for control purposes. The current state of the art are two-dimensional online calculations of the stock temperature [1,5]. In the model [5] the stock cross-section temperature field is calculated, while in the model [1] longitudinal section of the stock is treated in order to take into account skid-marks cooling. First attempts [6,7] have been made to calculate the stock temperature online in three dimensions. A 3D online simulation model of reheating in a walking-beam furnace is presented in [6]. An online 3D simulation model of pusher type furnace is reported in [7]. Both 3D models can be used for monitoring and control purposes.



Fig. 1 OFU walking-beam furnace at Štore Steel d.o.o.

The benefits of using real-time simulation model of reheating process in continuous furnace for the industry are: RT monitoring of individual stock

temperature fields during the reheating process, the heating process is documented for every stock heated in the furnace, the production of scrap due to improper heating can be minimized. The model can be used for optimization of heating rules for different steel grades and different stock dimensions. The model can be upgraded by the control system for tracing the reference heating curves of individual stock in the furnace.

In the paper the industrial application of recently implemented simulation model on walking-beam reheating furnace at Štore Steel d.o.o. is presented.

2 Walking-beam furnace

In the Štore Steel, d. o. o. steelworks a continuous walking-beam furnace (Fig. 1,2) is used for the reheating of steel billets (up to 220mm x 200mm cross-section) to the temperature suitable for hot rolling process (1220 – 1300°C). The length of the furnace is 31.5m and the furnace width is 4.7m. The material flow through the furnace is discontinuous, with fixed walking-beam steps.

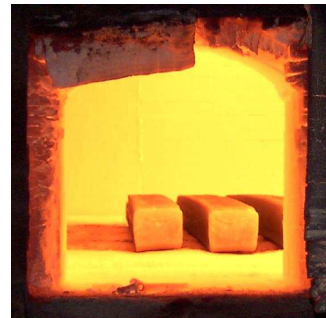


Fig. 2 Billets in the furnace (view through side door)

The furnace has 125 billet positions; The furnace is of gas-fired type and is by the length divided into three control zones: preheating, heating and soaking zone.

3 Modeling

Calculations in the model base on mathematical model, which includes main physical phenomena appearing during the reheating process in a natural-gas-fired walking-beam furnace. The real-time model is always the compromise between the quality of simulation results and calculation speed. With increasing computational power more and more complex algorithms can be used in real-time applications. The following models and algorithms are selected to allow real-time calculation of temperature fields of all (up to 126) billets in the furnace on Pentium 4 processors.

Heat conduction inside the billets is calculated in three dimensions by the finite-difference method. Boundary conditions on the billet surface are determined as total heat fluxes on the billet surface

\dot{q}_{total} . Note that the unit of \dot{q}_{total} is defined in $[\text{W}/\text{m}^2]$ of the charge surface area.

3.1 Determination of total heat flux on the billet surface

The furnace is along the length divided into the segments (i.e. 1m long). For each length segment the homogenous temperature field of furnace gasses is assumed. The heat exchange between the furnace wall, the furnace gas and the billet surface for the length segment is calculated using the three temperature model of Heiligenstaedt [8] (Figure 2).

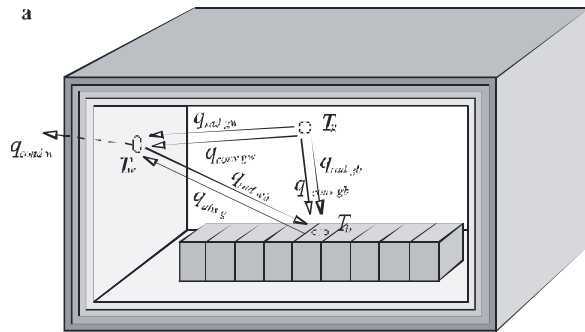


Fig. 3: The heat exchange between the furnace gas, furnace wall and the billet surface of the furnace length segment

The only unknown temperature in the system is furnace gas temperature ϑ_g , that can be evaluated by solving a equilibrium equation on the inner furnace wall (1).

$$0 = \dot{q}_{rad\ gw}(\vartheta_g, \vartheta_w) \cdot A + \dot{q}_{conv\ gw}(\vartheta_g, \vartheta_w) \cdot A - \dot{q}_{cond\ w}(\vartheta_w) \cdot A - \dot{q}_{rad\ wc}(\vartheta_w, \vartheta_c) \cdot a + \dot{q}_{abs\ g}(\vartheta_g) \cdot a \quad (1)$$

In the equation (1) A represents the area of wall surface, which surrounds the area of heated surface a . Once all three temperatures in the system are known, the total heat flux on the charge surface \dot{q}_{total} can be evaluated using equation (2).

$$\dot{q}_{total} = \dot{q}_{rad\ gc}(\vartheta_g, \vartheta_c) + \dot{q}_{conv\ gc}(\vartheta_g, \vartheta_c) + \dot{q}_{rad\ wc}(\vartheta_w, \vartheta_c) + \dot{q}_{abs\ g}(\vartheta_g) \quad (2)$$

Partial mechanisms of heat exchange used in equations (1) and (2) are unique in their complexities; they base on the gray-gas model of CO₂ and H₂O mixtures of Hottel [9]. Their calculation is described in detail in [7].

3.2 Thermal radiation of surfaces in the furnace enclosure

Thermal radiation is the main heat transfer mechanism in a high-temperature reheating furnace. The geometry of the furnace enclosure has an important role in thermal radiation heat transfer. Therefore the determination element $\dot{q}_{rad\ wc}$ in (1) and (2) which accounts exact furnace geometry is determined by the following procedure.

The furnace geometry including charged billets is divided into J smaller surfaces under assumption of isothermal surfaces (Fig. 4).

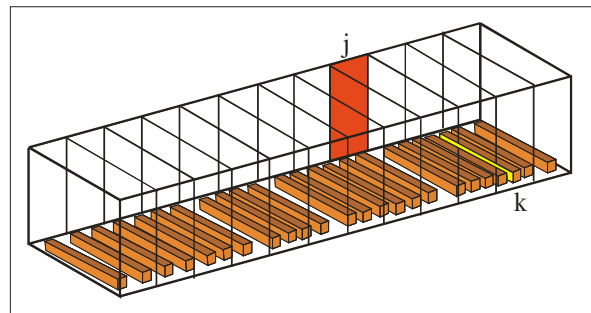


Fig. 4: The furnace enclosure with the charged billets

For the surface k in Fig. 4 it is possible to write heat balance $\dot{Q}_{k\leftrightarrow}$ as the difference between incoming $\dot{Q}_{k\leftarrow}$ and outgoing radiation $\dot{Q}_{k\rightarrow}$: [7]

$$\dot{q}_{rad\ wc,k} A_k = \dot{Q}_{k\leftrightarrow} = \dot{Q}_{k\leftarrow} - \dot{Q}_{k\rightarrow} = \sum_{j=1}^J [\varepsilon_j (T_j) \sigma T_j^4 A_j f_{j\rightarrow k}] - \varepsilon_k (T_k) \sigma T_k^4 A_k \quad (3)$$

The incoming thermal radiation $\dot{Q}_{k\leftarrow}$ consists of J thermal radiation contributions of individual surface elements j . In (3) are: ε emissivity of the surface, σ Stefan-Boltzmann constant ($5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$), T absolute temperature of the surface (K), A of the surface (m^2) and $f_{j\rightarrow k}$ view-factor which describes the fraction of the total thermal radiation emitted by surface A_j that is absorbed in surface A_k including multiple reflections. Since some of the surfaces in the enclosure can not view each other and some can be viewed just partly, the furnace enclosure presents complex geometry for view-factor calculation.

For the whole furnace geometry consisted of J surfaces the heat balance is written in a vector-matrix form:

$$\dot{Q}_{\leftrightarrow[J \times 1]} = \dot{Q}_{\leftarrow[J \times 1]} - \dot{Q}_{\rightarrow[J \times 1]} = \mathbf{F}_{[J \times J]} \cdot \dot{Q}_{\rightarrow[J \times 1]} - \dot{Q}_{\rightarrow[J \times 1]} \quad (3)$$

The heat balance vector $\dot{Q}_{\leftrightarrow[J \times 1]}$ for the whole furnace geometry can be calculated when the view-factor matrix F and outgoing thermal flux vector $\dot{Q}_{\rightarrow[J \times 1]}$ are known. The view-factor matrix F is determined before the simulation by Monte Carlo method.

The furnace geometry including charged billets is divided into J smaller surfaces under assumption of isothermal surfaces. For the surface k in Figure 3a it is possible to write heat balance $\dot{Q}_{k\leftrightarrow}$ as the difference between incoming $\dot{Q}_{k\leftarrow}$ and outgoing radiation $\dot{Q}_{k\rightarrow}$: [5]

3.3 Furnace floor temperature

Billets in the walking-beam furnace lie on the furnace floor. The furnace floor is reheated from other surfaces in furnace enclosure that can be furnace walls or billet surfaces. When the floor area covered by billets increases the furnace floor becomes colder.

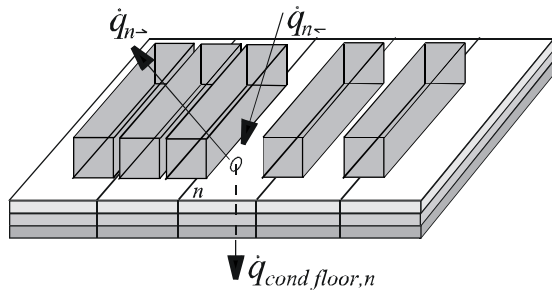


Fig. 5 Determination of furnace floor temperature

The furnace floor is by its length divided to K floor surface elements to fulfil isotherm condition. For each floor surface element k the heat flux balance equation is derived (Fig. 5):

$$\dot{q}_{k\leftarrow} - \dot{q}_{k\rightarrow} - \dot{q}_{\text{cond floor},k} = 0 \quad (4)$$

The calculation of all three thermal fluxes in equation (4) depends on the unknown temperature T_k of furnace wall element. The bisection method is used in the model to solve the balance equation (4) numerically, which gives the surface temperature of the furnace floor element T_n .

4 Validation

The model was validated on the basis of measurements from the OFU walking-beam furnace at the Štore Steel steelworks in Slovenia. The test billet (CK45 steel grade, dimensions 140 mm x 140 mm x 3500 mm) was reheated during the normal production process. The temperature measurements were performed using three trailing thermocouples (Type

K, $\phi = 4.5\text{mm}$, $L = 35\text{m}$). These three thermocouples were mounted inside a test billet, as shown in Figure 6. Thermocouple TC1 was mounted 10 mm under the upper slab surface; TC2 was mounted in the centre of the billet; and TC3 was mounted 10 mm from the bottom billet surface, 130 mm deep.

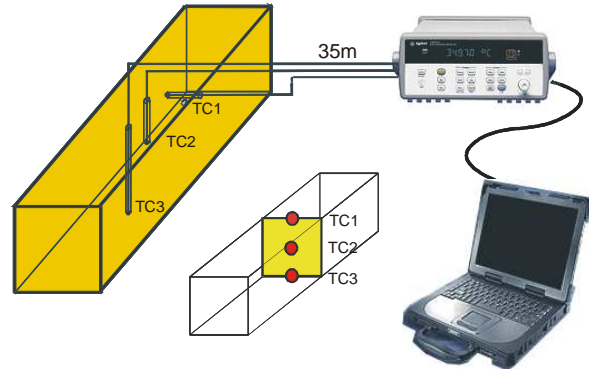


Fig. 6 Measuring points in the test billet

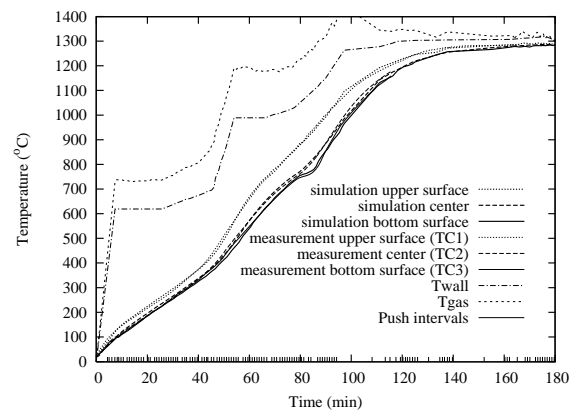


Fig. 7 Comparison between simulated and measured reheating curves

The simulation model was compared with the measurements at all three measuring points, TC1, TC2 and TC3. Good agreement was obtained between the measured and the calculated temperatures at all three comparison points for the whole reheating process (Figure 7). The small vertical lines at the bottom of the graph show the walking-beam step intervals of the furnace. The validation phase shows that the developed algorithms of the simulation model for billet reheating in the OFU furnace are in good agreement with the real physical behavior of the reheating process.

5 Implementation

The implementation of the simulation model for the online operation of the furnace includes the development of modules to provide real-time measuring data from the furnace, to provide and recognize the current furnace charge, to provide the thermal properties of different steel grades, to store the simulation results in a database, and to present the simulation results in a user-friendly form. The system is developed completely by using open-source

software. It runs under Suse Linux 10.2, the simulation model is written in C, “xforms” library is used for graphical user interface under Xwindow and MySQL is used for the database system. For the successful industrial application of the simulation model close cooperation between technologists, IT department and developers is needed together with the full support of management.

5.1 Obtaining the real-time data

For the online operation of the simulation model the real-time data of furnace charging and furnace measurements are needed. The computer with the simulation model is connected to the existing furnace-process computer of the OFU furnace (Fig. 8), which provides the real-time data. Both computers are connected by an Ethernet connection. The data transfer is performed with ASCII files using file-transfer protocol (FTP).

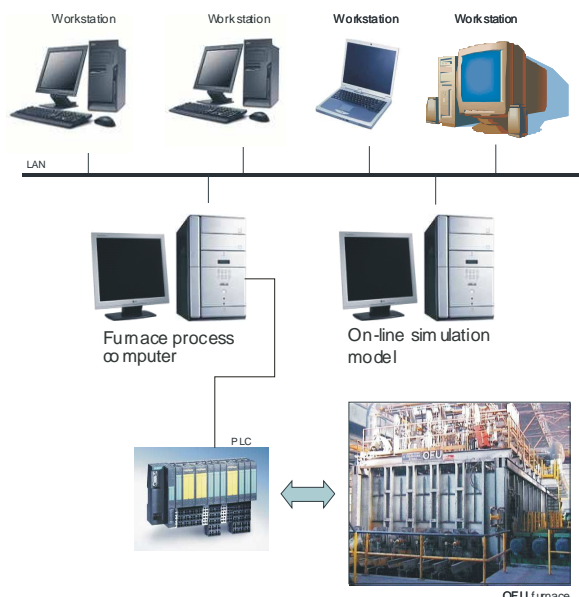


Fig. 8. The connection of the simulation model to the OFU furnace-process computer

5.2 Material Thermal properties data

The thermal properties (the specific heat and the heat conduction) of steel billets have a significant influence on the reheating process. Generally speaking, these properties are temperature dependent. In the production process different steel grades with different thermal properties are reheated in the furnace; however, some of them have similar thermal properties. Therefore, all types of steel grades are classified into main groups, and for these groups the thermal properties were measured or obtained from the literature. The automatic classification is based on a uniform classification table.

5.3 Recognition of the charging events

The system is capable of automatic recognition of the charging events and the charging interventions of the furnace operator on the basis of a comparison between

the billet-charging table and the charging file. At the end of the event-recognition process the charging table and charging file have to be harmonized. The recognition of charging events is a three-stage process. The three stage recognition process will be presented in the final paper

5.4 Database structure

All the results of the simulation model are stored in a local database named “ofu” (Fig. 9). The system uses the open-source database system MySQL. The database can be accessed locally by the online simulation model and the graphical-user interface (GUI) or through an Ethernet connection by PC workstations in the local area network (LAN).

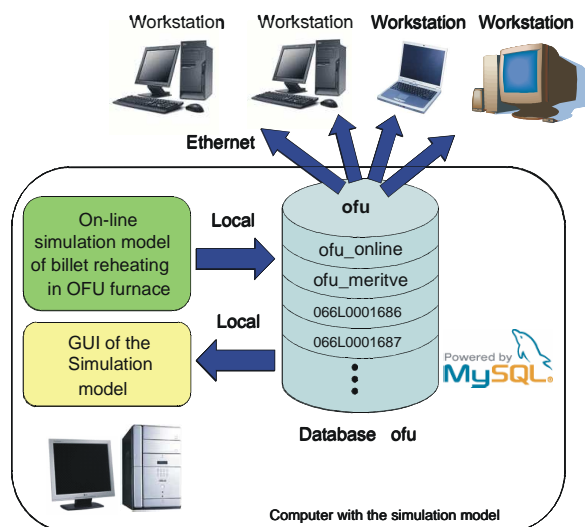


Fig 9. Database organization

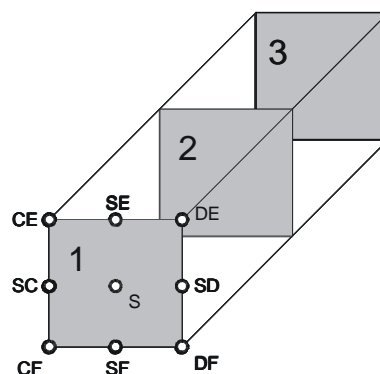


Fig. 10. Characteristic points on the billet cross-sections

The database consists of data tables. At every simulation step (30seconds) the simulation model refreshes the data table “ofu_online” (Fig. 9). The records in the table correspond to the billets in the furnace. Each record in the table includes basic billet data (Working order, Serial number in the working order, Steel grade, Billet width, Billet height, Billet length, Charging time, Real-time of last calculation, Number of the walking-beam step, Position in the

furnace, Residing time at the position, Residing time in furnace) and the characteristic points of the last-calculated temperature field of the billet (Fig. 10).

5.5 Graphical-user interface

The graphical-user interface (GUI) (Fig. 11) was developed for the user-friendly presentation of the real-time results of the simulation model.

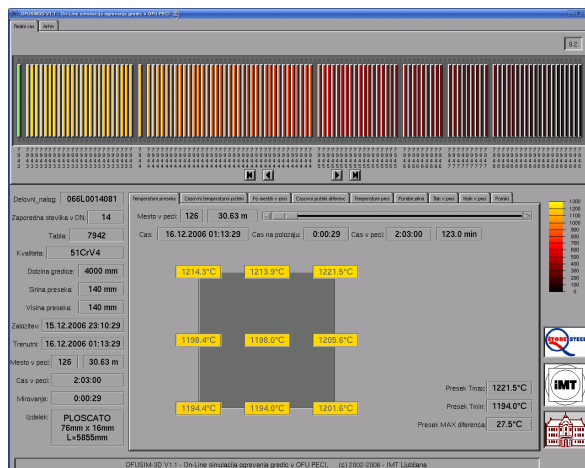


Fig. 11. The GUI of the simulation model – calculated temperatures of characteristic points of the middle cross-section for the selected billet (green)

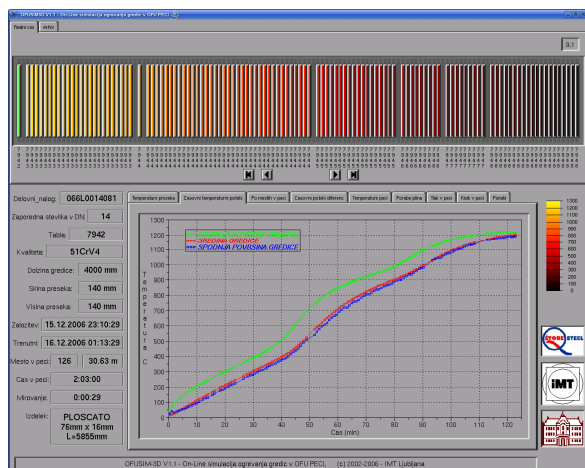


Fig. 12. The GUI of the simulation model – calculated temperatures (billet upper surface, billet center and billet bottom surface) for the selected billet (green).

The GUI process runs parallel to the simulation model. The GUI gets all the data from the “ofu” database. There are two modes of GUI operation: real-time and archive.

When the GUI runs in real-time mode the top view of the furnace containing charged billets is shown in the upper part of the window (Fig.11). The reheating history of the selected billet is presented in Fig. 12.

6 Conclusions

The implemented system allows online monitoring of non-measurable values (the 3D temperature fields of billets in the furnace) for all billets in the furnace. The complex physical phenomena at heat exchange in the gas-fired furnace, including complex geometry of furnace enclosure is treated in the model. The algorithms used in the model are selected as a compromise between the accuracy of the results and the calculation speed in order to allow application for on-line operation.

Good agreement between the measured and the calculated heating curves shows that the model includes the main physical phenomena occurring during the reheating process in the OFU walking-Beam furnace.

The system is connected to the furnace-process computer to ensure real-time measuring and charging data from the furnace. The simulation model's results are stored in an SQL database, which allows internet access to the data. The developed graphical user interface allows a user-friendly presentation of the simulation model's results. The system has been used online for monitoring production process at the Štore Steel, d. o. o., steelworks in Slovenia since May 2006.

The applied real-time model is planned to be used as a part of the control system for tracing the reheating curves.

7 References

- [1] P. Marino, A. Pignotti and D. Solis. Numerical model of steel slab reheating in pusher furnaces. *Latin American Applied Research*, 32:257-261, 2002.
- [2] T. Kolenko, B. Glogovac, A. Jaklič. An analysis of a heat transfer model for situations involving gas and surface radiative heat transfer. *Commun. numer. methods eng.*, 15:349-365 (2002).
- [3] D. F. J. Staalman. Process control in reheating furnaces. *IoM conference Challenges in Reheating Furnaces*, Conference Papers, 267-285, London, 2002.
- [4] Z. Chen, C. Xu, B. Zhang, H. Shao and J. Zhang. Advanced control of walking-beam reheating furnace. *Journal of University of Science and Technology Beijing*, 4:69-74, 2003.
- [5] B. Leden. STEELTEMP[®] for temperature and heat-transfer analysis of heating furnaces with on-line applications, *IoM conference Challenges in Reheating Furnaces*, Conference Papers, 297-307 London, 2002.
- [6] Jaklič, T. Kolenko, B. Glogovac. A real-time simulation model of billet reheating in the

Allino walking-beam furnace. *Proceedings of international conference: Refractories, Furnaces and Thermal Insulations*, Košice, 237-242, 2004

- [7] Jaklič, F. Vode, T. Kolenko. Online simulation model of the slab-reheating process in a pusher-type furnace. *Applied Thermal Engineering*, 5-6:1105-1114, 2007.
- [8] W. Heiligenstaedt. *Waermetechnische Rechnungen fuer Industrieoefen*, Verlag Stahleisen M.B.H, Duesseldorf, 1966.
- [9] H.C. Hottel H. : *Heat Transmission*, 3edn., W. H. McAdams (Ed.) McGraw-Hill, New York 1954.