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THE IMPLEMENTATION OF AN ONLINE MATHEMATICAL MODEL OF SLAB REHEATING IN A PUSHER-TYPE FURNACE

IMPLEMENTACIJA ON-LINE MATEMETIČNEGA MODELA OGREVANJA SLABOV V POTISNI PEČI

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In this paper the implementation of an online mathematical model of slab reheating in a pusher-type furnace at the Acroni, d. o. o., steelworks in Slovenia is presented. The simulation model is connected to the existing information system of a hot-rolling plant that can ensure the required data for the simulation model online. The simulation is performed for all the slabs that are currently charged in the furnace. In order to validate the model, measurements of the slab reheating in the pusher-type furnace were made. The measurements were performed on a test slab using trail thermocouples. The comparison of the measurements and the simulation results shows good agreement across the whole temperature range of the reheating process. For a user-friendly presentation of the simulation model results a graphical user interface (GUI) was developed. The GUI allows the selection of a particular slab from the figure of currently charged slabs. The temperature field and the history of the reheating by individual positions of the slab in the furnace are shown for the selected slab. This online system has been used in the regular production process since September 2004.

Key words: simulation of reheating, slab reheating, real-time simulation, reheating furnace, pusher furnace

V prispevku je predstavljena implementacija on-line matematičnega modela ogrevanja slabov v potisni peči, ki je bila izvedena v Acroniju, d. o. o. Simulacijski model je povezan na informacijski sistem vroče valjarne, ki omogoča dostop on-line do podatkov, potrebnih za simulacijo. Simulacija se izvede za vse založene slabe v peči hkrati. Simulacijski model je bil ovrednoten z meritvami temperaturnih potekov ogrevanja preskusnega slaba, ki so bile izvedene z vlečnimi termoelementi. Za uporabniško prijazen prikaz izračunanih vrednosti je bil razvit grafični uporabniški vmesnik. Ta omogoča izbiro želenega slaba na prikazu založitve peči. Za izbrani slab omogoča prikaz njegovega trenutnega temperaturnega polja in njegove zgodovine ogrevanja po posameznih pomikih v peči. Sistem je vključen on-line v redni proizvodni proces od septembra 2004.

Ključne besede: simulacija ogrevanja, ogrevanje slabov, simulacija v realnem času, ogrevna peč, potisna peč

1 INTRODUCTION

The purpose of a reheating furnace is to supply heated slabs with a uniform temperature distribution in the required range to the hot-rolling mill. During steady-state operation of the furnace, where the reheating history of every slab is very similar, this aim can normally be achieved. Various reasons, such as planned and unplanned stoppages in the mill's operation, changing steel grades with varying drop-out temperatures and different thermodynamic properties, and changing stock dimensions, cause transient operation of the furnace. During transient operation every stock is reheated under different reheating conditions. Therefore, the reheating history of almost every stock is different. With transient furnace operation a knowledge of the temperature field of the stock during the reheating process is very important for successful furnace control and operation. The existing measuring methods cannot provide temperature fields of the slabs in the furnace. However, using trailing thermocouples it is possible to measure the reheating at a few measuring points inside the slab, but this can just be used on the test slabs. Measurements using optical pyrometers or thermal cameras in the furnace only give information about the surface temperature of the stock. This means that the use of an online simulation model seems to be the most reasonable way to acquire the real-time temperature field of the stock in the furnace.

In the Acroni, d. o. o., steelworks a pusher-type furnace (**Figure 1**) is used for the reheating of the steel slabs. The furnace has six control zones: the upper and lower preheating zones, the upper and lower heating zones, and the left- and right-hand soaking zones. The material flow through the furnace is discontinuous, with the movement happening in push steps. At each push step the pushing machine pushes all the slabs until the slab at the exit does not drop out from the furnace. The length of the pushing step depends on the width of the discharged slab. The number of slabs inside the furnace can vary and depends on the width of the individual slabs.

In the past 10 years the simulation models which were able to calculate the actual temperature distribution

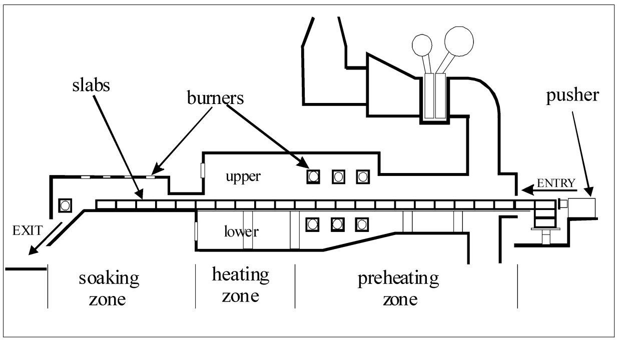

Figure 1: Pusher-type furnace
Slika 1: Potisna peč

in the stock were developed with the increasing computational power. The state of the art is a one- or two-dimensional calculation of the stock temperature [1,2,3,4]. However, initial attempts have been made to calculate the stock temperature in three dimensions [5,6,7] for different types of reheating furnaces, but not in real-time. The 3D online simulation model of reheating in a walking-beam furnace is presented in [8]. In this paper we would like to present an implementation of an online simulation model of a pusher-type furnace. By using a 3D simulation model it is possible to account for the effects of skid pipes and the temperatures of the slab edges.

2 EXPERIMENTAL WORK

The implementation of the mathematical model of the furnace includes the development of modules to provide real-time data from the furnace, to recognize current furnace charging to provide the thermal properties of different steel grades and to present the simulation model results in a user-friendly way.

2.1 Mathematical model

The online mathematical model used in the implementation is presented in detail in [8,9]. The calculations in the model are based on algorithms that include the main physical phenomena appearing during the reheating process in a natural-gas-fired pusher-type furnace. The dominant contribution to heat transfer in a high-temperature reheating furnace is represented by thermal radiation. The heat exchange between the furnace gas, the furnace wall and the billet surface is calculated using the three-temperature model of Heiligenstaedt.[10] The heat radiation between the surfaces inside the furnace is described using a view-factor matrix. This matrix is obtained before the simulation using the Monte Carlo method. The heat conduction in the slabs is calculated using the 3D finite-difference method. The algorithms in the model are optimized to allow a real-time simulation.

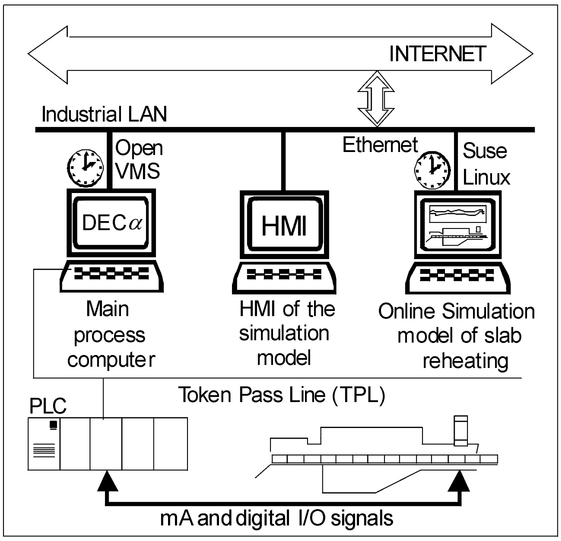

Figure 2: The connection of the simulation model to the information system of the hot-processing plant
Slika 2: Povezava simulacijskega modela v informacijski sistem vroče valjarne

2.2 Obtaining real-time data

For online operation of the simulation model real-time data from the furnace charging and the furnace measurements are needed. The simulation model is connected to the existing information system of a hot-processing plant (**Figure 2**), which provides the real-time data about the furnace charging and measurements in the furnace. The main information computer in the hot-processing plant is a DEC Alpha. The computer with the simulation model is connected to the main information computer by an Ethernet connection. The data transfer is performed using ASCII files using file-transfer protocol (FTP).

The measurement data are written every 60 seconds by the main information computer to the file "MEASUREMENTS.DAT". These data are:

- Date and time of measurements
- Temperature measurements of six control zones
- Gas/air flows of individual control zones
- Five oxygen measurements
- Pressure measurements
- Measurements of recuperator temperatures.

The charging data are written to the file "CHARGING.DAT" as the list of all slabs currently placed in the furnace. The file is written when a change of the state of the charging in the furnace occurs. The events that change the state of the charging are: a push event, a discharge of the slab and an addition of new slabs to the furnace. Besides normal events, the operator can manually delete, add or change the position of an individual slab in the charging list. The charging data in the file are written in a table form with all the slabs that are currently in the furnace. The data of the individual slabs in the table consist of:

- Slab ID
- Slab steel grade
- Slab dimensions
- Slab weight
- Date and time of charging

Both the "MEASUREMENTS.DAT" and "CHARGING.DAT" are transferred from the main information computer to the computer with the simulation model at regular intervals (i.e., 50 s) by FTP, which runs on the computer with the simulation model. After the transfer the data are deleted from the main process computer. The intervals of transferring the data files have to be shorter than the intervals of writing the data to the files in order to prevent data loss.

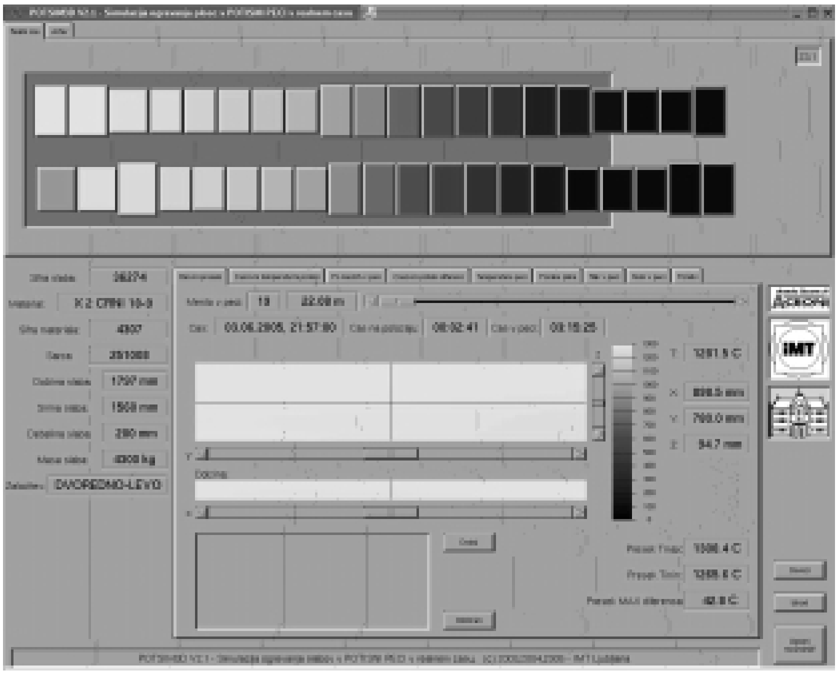

Figure 3: The Human-Machine Interface of the simulation model – review of slab temperatures using a thermal color scale
Slika 3: Grafični uporabniški vmesnik simulacijskega modela – prikaz temperature slaba s toplotno barvno lestvico

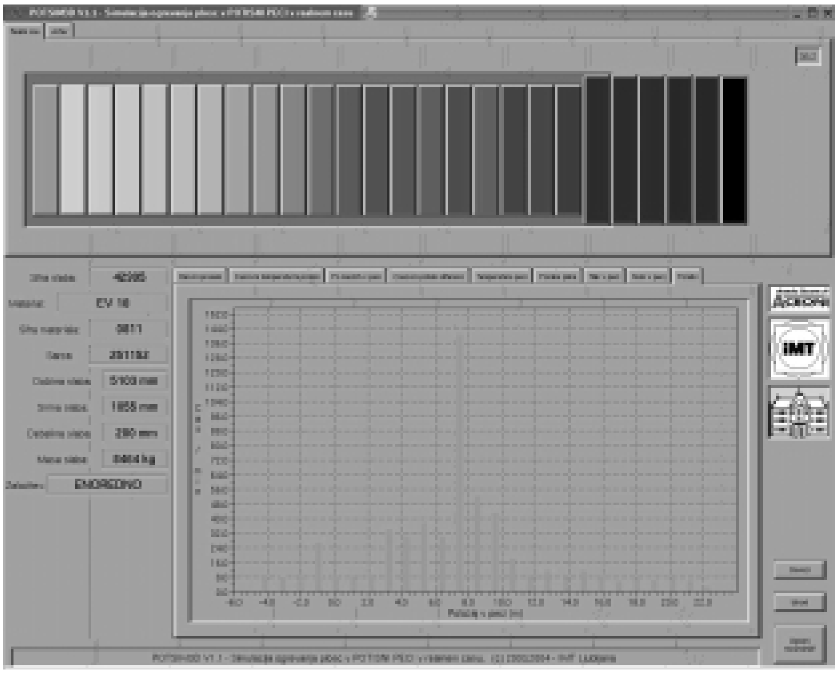

Figure 4: The Human-Machine Interface of the simulation model – diagram of the holding time of the slab at the individual position in the furnace
Slika 4: Grafični uporabniški vmesnik simulacijskega modela – diagram časa zadrževanja slaba na posameznem mestu v peči

2.3 Thermal properties data

The thermal properties – specific heat and heat conduction – of the steel slabs have a significant influence on the reheating process. Generally, these properties are temperature dependent; in the model they are written as tables in ASCII files. In the production process, different steel grades with different thermal properties are reheated in the furnace (more than 300), but some of them have similar thermal properties. Therefore, the whole range of steel grades is classified into eight main groups. For these groups the thermal properties were measured or obtained from the literature. The automatic classification is based on the uniform classification table, where the corresponding steel group is written for each steel grade in the table. When the slab is added to the charging list the corresponding steel group is recognized on the basis of the slab steel grade. The system then reads from the files the temperature-dependent specific heat and heat conduction tables for the appropriate steel group. These data are then used in the calculation of the thermal conduction inside the slab.

2.4 Automatic recognition of charging events

The system is capable of automatic recognition of charging events and the furnace operator charging interventions on the basis of a comparison between the slab charging table and the charging file. At the end of the event-recognition process the charging table and the charging file have to be harmonized. The recognition of charging events is a three-stage process.

In the first stage every slab in the charging table is tested for presence in the charging file. The slabs for which the test fails are deleted from the charging table and their reheating history is saved in the archive directory.

In the second stage every slab in the charging file is tested for presence in the charging list. The slabs for which the test fails are added to the charging list and a new file with the slab data is opened and filled with the initial data.

After the first and the second stages the same slabs are included in the charging list and in the charging file. In the third stage the slabs in the charging list are sorted in the same order as in the charging file. The position of every slab in the charging list is compared to that in the charging file. If the position is different, then the position in the list is changed and the current calculated temperature field and the position data are written in the reheating file of that slab. The same algorithm is used for single and for double charging and also for transitional operations: single-to-double and double-to-single charging.

2.5 Human-Machine Interface

The Human-Machine interface (HMI) (**Figure 3**) was developed for the user-friendly presentation of the real-time simulation-model results. The HMI process runs in parallel with the simulation model. The data from both programs are exchanged using dynamically refreshed ASCII files. The HMI runs in the Real-time or the Archive mode.

When the HMI runs in real-time mode the top view to the furnace with the charged slabs is shown in the upper part of the window (**Figure 3**). The slab is selected with a mouse click. In the lower part of the window are the detailed data of the selected slab: Slab ID data, steel grade, dimensions, etc. The calculated temperature field of the selected slab is presented with three sections using a thermal scale. The individual slab element can be selected by vertical and horizontal sliders. Different diagram presentations, such as the reheating temperatures of three selected points in the slab, the temperatures of individual furnace control zones, the gas consumption of individual control zones, the measurement of oxygen, the pressure in the furnace, the holding time of the slab at individual positions (**Figure 4**) in the furnace, can be selected. The Archive mode allows a preview of the reheating process of already-reheated slabs. The slabs in the archive list are sorted in terms of discharge time. The HMI is developed using the XFORMS graphical library.

3 RESULTS AND DISCUSSION

The model was validated on the basis of measurements made on the pusher furnace at the Acroni Steelworks in Slovenia. The measurements were performed using five trailing thermocouples (Type K, d = 6 mm, L = 30 m). These five thermocouples were mounted on a test slab, as shown in **Figure 5**. Thermocouple TC1 was mounted 10 mm under the upper slab surface, TC2 was mounted in the slab centre, TC3 was mounted 10 mm above the bottom surface, TC4 and TC5 were mounted on the slab surface.

The first measurement was performed on a test slab (material: AISI 316L, thickness 200 mm). The temperatures were measured during the reheating of the slab as it passed through the furnace. The simulation model was compared with the measurements at three points, TC1, TC2 and TC3. The tuning of the model was performed

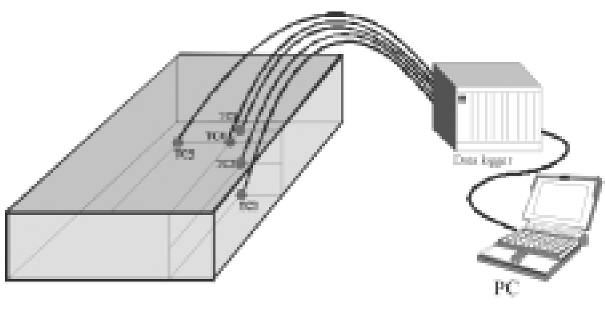

Figure 5: Measuring points in the test slabs
Slika 5: Merilne točke na preskusnem slabu

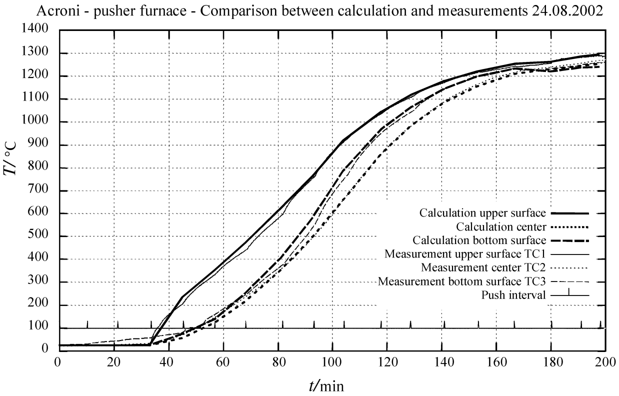

Figure 6: Validation of the simulation model for the test slab (material: AISI 316L, thickness 200 mm) after the tuning of the model
Slika 6: Vrednotenje simulacijskega modela na preskusnem slabu (material: AISI 316L, debeline 200 mm) po uglasitvi modela

by adjusting the temperature profile of the furnace's ceiling and sidewalls. After the tuning of the model, all the parameters of the model were within the real physical values. Good agreement was obtained between the measured and the calculated temperatures at all three comparison points for the whole reheating process (**Figure 6**). The small vertical lines at the bottom of the graph show the push intervals of the furnace.

The second measurement was performed on a test slab (material: AISI 316L, thickness 250mm). The temperatures were again measured during the reheating of the slab as it passed through the furnace. The heating curves of the already-tuned simulation model were compared with the measurements at three points, TC1, TC2 and TC3. Good agreement was obtained between the measured and the calculated temperatures, even if the test slab had a different thickness (**Figure 7**).

The validation phase shows that the developed algorithms of the simulation model for slab reheating are in good agreement with the real physical behaviour of the reheating process.

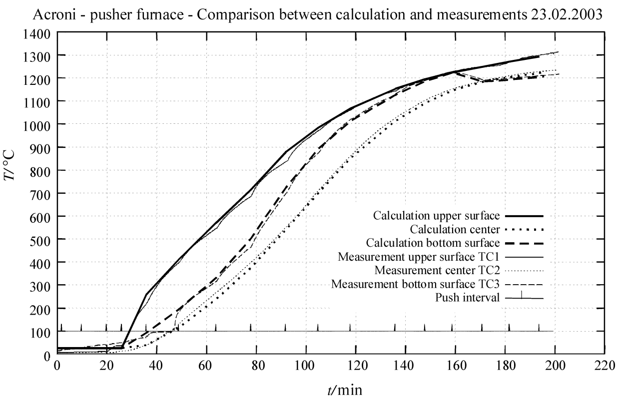

Figure 7: Validation of the already-tuned simulation model for the test slab (material: AISI 316L, thickness 250 mm)
Slika 7: Vrednotenje že uglašenega simulacijskega modela na preskusnem slabu (material: AISI 316L, debeline 250 mm)

Figure 8: On-line simulation model on the operator desk of the pusher-type furnace
Slika 8: Simulacijski model na komandnem pultu v merilni kabini potisne peči

The system was developed using entirely open-source solutions. The Linux platform ensures stable running of the system. The system has been used online in the regular production process since September 2004 (**Figure 8**). During this time the system has stopped a few times. Every such event was extensively analyzed to prevent future stoppages. We found that the main reason for the stoppages was problems with the charging data, where there were slabs with the same ID written in the charging file. During this time the charging module of the system was improved to ensure robustness of the system according to charging data.

4 CONCLUSIONS

The implemented system allows online monitoring of non-measurable values (3D temperature fields of slabs in the furnace). The system is connected to the information system of a hot-processing plant to ensure real-time measuring and charging data from the furnace. 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 pusher-type furnace. The developed HMI allows a user-friendly presentation of the simulation model results. The system has been used online in the regular production process at Acroni, d. o. o., since September 2004.

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