POSSIBILITIES FOR SAVING ENERGY IN FERROUS METALLURGY
Integration of Technological Processes

by

Emil MIHAILOV*, Venko PETKOV, Mariya IVANOVA, and Blagoyka STOYANOVA

Physical Metallurgy and Thermal Equipments, University of Chemical Technology and Metallurgy, Sofia, Bulgaria

Original scientific paper
DOI: 10.2298/TSCI140218080M

One of the main factors having a significant effect on fuel and energy saving in the production of rolled ferrous metals is matching the operation of the continuous casting machines with that of the re-heating furnaces so called continuous technologies in the form of direct rolling or hot charging. In order to investigate the heat exchange processes, the opportunities for enhancing the energy efficiency and determining the optimal parameters of the flat product production process in ferrous metallurgy, some mathematical models of metal solidification and cooling in a continuous steel casting machine were determined as well as a mathematical model of metal heating in the re-heating furnaces. For efficient implementation of such technologies one common algorithm was built on the basis of the individual mathematical models, representing the continuous casting – rolling mill complex control technology, dynamically matching the operation of the individual units to the actual production conditions in on-line mode. The developed algorithm can be used as part of a system for analyzing the thermal condition of the blocks at any single moment for the purpose of optimization of the units' operation within the whole technological process. As a conclusion, considering the original developed algorithm, a 21-51% energy saving was noticed.

Key words: *mathematical model, heat transfer, hot charging, energy efficiency, re-heating furnaces, continuous casting*

Introduction

The analysis of feasible measures for energy efficiency improvement in the production of ferrous metals shows that a key factor with significant effect on the economy of fuel and energy is the use of machines for continuous steel casting (MCSC) and matching of their operation to that of the heating furnaces serving the roller mills [1]. To that end, a basic approach resulting in energy saving is to raise the temperature of the metal charged in the heating furnaces and eliminate the need for intermediate heating through implementation of the so-called *continuous technologies* introduced in the practice of leading producers in the form of *direct rolling* or *hot charging* [2]. Implementation of such technology is only possible in the presence of an up-to-date control system, which includes [1-3]: rational planning, development of time schedules of the operations, and a system for monitoring of the metal and determining the thermal condition of each individual block over time.

* Corresponding author; e-mail: emil@uctm.edu

Depending on the level of production organization, the following set-ups are possible [4] (see fig. 1):
– continuous casting – rolling with cold charging,
– continuous casting – rolling with hot charging,
– continuous casting – rolling with direct hot charging, called *hot charging*, and
– continuous casting – direct rolling.

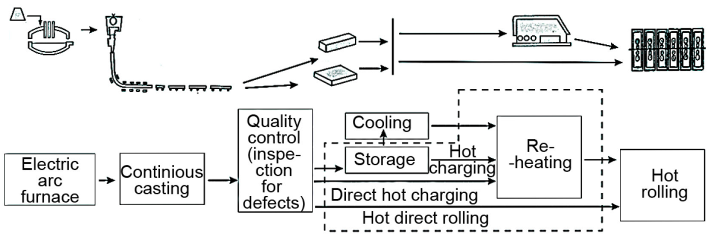

Figure 1. Production organization set-ups

The most important prerequisite for efficient implementation of *hot charging* is casting of blocks of guaranteed good quality, free of flaws, which would permit their charging into the heating furnaces without quality inspection and surface cleaning [3]. During hot charging, the blocks are conveyed to the heating furnaces with a high mean temperature, without intermediate stands or cooling.

Implementation of that method involves both technological and organizational measures, the most important ones being full synchronization of the processes and quality of the cast blocks. For this purpose, a metal tracking system has to be developed taking into account the particular thermal condition and temperature profile of the metal during the transport operations. Implementation of such a system involves knowledge of the temperature field of the blocks from the moment of their forming to their charging in the furnaces for pre-deformation heating, taking into account the processes of block solidification and cooling in the continuous casting process using optimal cooling modes ensuring production of high-quality blocks with maximum heat contents [3].

These results can be obtained by means of numerical implementation of an algorithm which includes [5]: (a) a mathematical model to describe heat transfer and solidification of the block during continuous steel casting, (b) a mathematical model describing heat transfer taking into account cooling of the metal, depending on the schedule and type of operations for transport of the blocks to the heating furnaces, and (c) a mathematical model for heat transfer and metal heating in the re-heating furnaces.

For optimal control of the whole technological process with on-line procedures, a generalized algorithm working in on-line mode has to be developed taking into account the temperature condition of the individual block, depending on the specific production conditions and technological preparedness of the individual units.

Mathematical modelling of heat transfer in the processes of continuous casting – rolling mill complex

Mathematical modelling of the block forming processes in continuous steel casting

The general differential equation of heat conduction with internal heat source [6-8] is used to describe the heat exchange process during solidification of the metal in continuous casting machines (CCM):

$$\rho_{\text{eff}}(T)C_{\text{eff}}(T)\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left[\lambda_{\text{eff}}(T)\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_{\text{eff}}(T)\frac{\partial T}{\partial y}\right]. \tag{1}$$

The effective values of density, specific heat, and heat conductivity can be presented:

$$\rho_{\text{eff}}=\psi_{\text{S}}\rho_{\text{S}}+(1-\psi_{\text{S}})\rho_{\text{L}} \tag{2}$$

$$C_{\text{eff}}=\begin{cases} C_{\text{L}}(T) & \text{for} \quad T_{\text{L}}>T \\ C(T)-\dfrac{\partial \psi_{\text{S}}}{\partial T}L_s & \text{for} \quad T_{\text{S}}^{*}<T<T_{\text{L}} \\ C_{\text{S}}(T) & \text{for} \quad T<T_{\text{S}}^{*} \end{cases} \tag{3}$$

$$\lambda_{\text{eff}}=[1+6(1-\psi_{\text{s}})^2]\lambda \tag{4}$$

where

$$\psi_{\text{S}}=\frac{1}{1-2\Omega k}\left[1-\left(\frac{T_0-T}{T_0-T_{\text{L}}}\right)^{\frac{1-2\Omega k}{k-1}}\right] \quad \text{and} \quad \frac{\partial \psi_{\text{S}}}{\partial T}=\frac{1}{k-1}(T_0-T_{\text{L}})^{\frac{2\Omega k-1}{k-1}}(T_0-T)^{\frac{2-2\Omega k-k}{k-1}} \tag{5}$$

The following initial and boundary conditions are used for solution of the heat conduction equation with 2-D co-ordinates and recognition of symmetry for 1/4 of the block cross section:

$$\begin{aligned} T(x,y,\tau)_{\tau=0} &= T_C(x,y) \\ -\lambda_{\text{eff}}(T)\left.\frac{\partial T}{\partial x}\right|_{x=0} &= q_1(y,\tau) \\ \lambda_{\text{eff}}(T)\left.\frac{\partial T}{\partial y}\right|_{y=S_2} &= 0 \\ \lambda_{\text{eff}}(T)\left.\frac{\partial T}{\partial x}\right|_{x=S_1} &= 0 \\ -\lambda_{\text{eff}}(T)\left.\frac{\partial T}{\partial y}\right|_{y=0} &= q_2(x,\tau) \end{aligned} \tag{6}$$

For the mold region the thermal flux is represented by:

$$q_i=h_m(T_{\text{M}}-T_{\text{W}}), \quad i=1,\ 2 \tag{7}$$

In the secondary-cooling zone (SCZ) q_i is determined by:

$$q_i=h_{\text{C}}(T_{\text{M}}-T_{\text{W}})+\sigma_0\varepsilon_{\text{M}}T_{\text{M}}^4, \quad i=1,\ 2 \tag{8}$$

In the zone of radiation heat transfer the thermal flux is described by:

$$q_i = \sigma_0 \varepsilon_\mathrm{M} T_\mathrm{M}^5, \quad i = 1,\ 2 \tag{9}$$

For low-carbon steel the determined cooling parameters shall meet the following requirements that are used as constraints in the development of optimization procedures in the computing algorithm [9-11].

– The shell thickness at the mold outlet and in the individual SCZ shall not be less than a definite permissible value securing failure-free operation.
– The liquid phase penetration depth (metallurgical length) shall not be too long – solidification shall end in SCZ, before the block has been subjected to deformation by the drawing rolls.
– The maximum cooling rate in SCZ shall be lower than 80 °C/m.
– The maximum through heating on the surface after emerging of the block from SCZ shall be lower than 50 °C.

According to previous requirements, the temperature distribution, the required heat flow values on the surface and the related heat transfer coefficients shall be defined for each of the cooling zones. For this purpose, additional iterative computing procedures are developed. The relation between the values of heat transfer coefficients and the parameters of the cooling jets for a specific nozzle design is determined experimentally in laboratory conditions.

Mathematical model of heat transfer during transport operations

For selection of the optimal heating modes in the heating furnaces an assessment has to be made, involving the thermal condition of the blocks and knowledge of the temperature field of each of them from the outlet of CCM to its charging in the heating furnaces. This process is depending on the type of transport operations and is taking into account its particular location when the blocks are stacked one upon another to be loaded for transportation, during transport, and after their unloading in the rolling shops.

The heat transfer between the individual blocks and between the blocks and the environment during transport and standing shall be evaluated taking into consideration the following transport operations (fig. 2):

– transportation of the blocks from the gas cutting machine,
– storage and stacking,
– loading on railway cars whereupon the blocks are rearranged,
– transportation,
– unloading and storage in the open air or in thermal boxes, whereupon the blocks are rearranged again, and
– charging of the blocks in the heating furnaces.

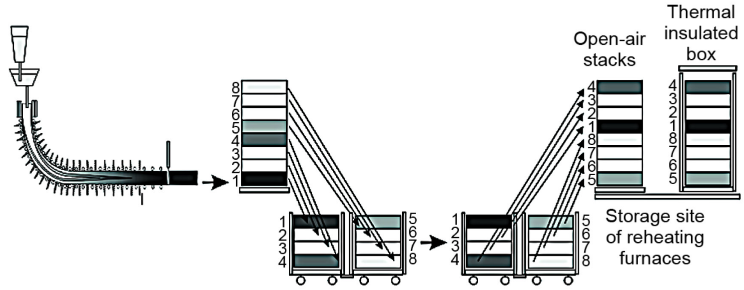

Figure 2. Position of the blocks during transport and standing in the rolling shop
1-8 – number of blocks

The mathematical modelling of cooling of the metal downstream of CCM is reduced to solution of a 2-D equation of heat conduction:

$$\rho(T)C(T)\frac{\partial T}{\partial \tau}=\frac{\partial}{\partial x}\left[\lambda(T)\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda(T)\frac{\partial T}{\partial y}\right] \tag{10}$$

in the respective initial and boundary conditions. The initial temperature distribution in the blocks is determined on the basis of computations with the mathematical model of metal cooling in MCSC. The boundary conditions are determined by means of zonal method of external heat exchange for each transport operation. Due to existing symmetry the numerical analysis is carried out for half of the cross section of the blocks. The initial and boundary conditions for the blocks inside the stack have the following form:

$$\begin{aligned}
&T(x, y, \tau)_{\tau=0}=T_{\mathrm{cc}}(x, y)\\
&-\lambda_{\mathrm{eff}}(T)\frac{\partial T}{\partial x}\bigg|_{x=0}=q(y, \tau)\\
&\lambda_{\mathrm{eff}}(T)\frac{\partial T}{\partial y}\bigg|_{y=2S_2}=h_{\mathrm{tcc}}(T_{\mathrm{M2}}-T_{\mathrm{M1}})\\
&\lambda_{\mathrm{eff}}(T)\frac{\partial T}{\partial x}\bigg|_{x=S_1}=0\\
&-\lambda_{\mathrm{eff}}(T)\frac{\partial T}{\partial y}\bigg|_{y=0}=h_{\mathrm{tcc}}(T_{\mathrm{M1}}-T_{\mathrm{M2}})
\end{aligned} \tag{11}$$

For the top surface of the stack the boundary condition looks:

$$\lambda_{\mathrm{eff}}(T)\frac{\partial T}{\partial y}\bigg|_{y=2S_2}=q(y, \tau) \tag{12}$$

where q is determined by eq. (9).

Monitoring of the heat exchange processes in the blocks during transport operations and standing in the rolling shop permits to determine their thermal condition and their temperature field at the inlet of the heating furnaces.

Modelling of the heat exchange processes in pre-deformation metal heating

The purpose of pre-deformation heating is bringing of the metal to a preset final temperature at a permissible temperature gradient before it leaves the furnace. This operation needs an optimization of the fuel consumption and of the quantity of oxidized metal at the actual rate of rolling, respectively.

Equation (10) is used to determine the temperature field inside the bulk of metal and its solution along with the respective boundary conditions, shall be checked. The resultant heat flux incident on the metal surface is used as a boundary condition for solution of the heat conduction equation describing the temperature distribution across the metal section.

The algorithm of solution of the problem of metal block heating includes [5, 12]:

– determining of the velocity, temperature and concentration fields in the bulk zones at a given moment considering parameters of the air and gas for the respective design of fuel combustion facilities [13],
– solution of the radiation heat exchange problem giving the boundary conditions [14]; the net heat flow falling on the surface of the metal is used as a boundary condition for solution of the heat conduction equation describing the temperature distribution; the sum of the emitted radiation value and the heat flow reflected from the same surface represents the effective heat flow; the method of zones is used in the determination of boundary conditions required for solution of heat conduction equation to describe the radiation heat transfer; by means of this method, the thermal flows emitted and absorbed by the hot gases and all surfaces participating in the heat transfer have to be determined, and
– computation of the temperature field in the metal and in the furnace refractory insulation under the defined initial and boundary conditions [15, 16].

The description of the mathematical model in detail is presented in [12].

Results and discussion

The operating parameters of radial CCM with radius of the radial area 12 m, length of the mold 1,2 m and technological length 24.3 m are the object of the present work. The main constructive dimensions of SCZ are presented in tab. 1, where with *R* and *r* the big and the small radius of the machine are marked.

The mathematical model is used in parallel with determining the values of heat transfer coefficients, the results for the temperature field may be used for adjustment of the zones from the surface of the block in SCZ that should be covered directly by the water jets. The results and information on water jet parameters obtained by laboratory experiments [17] are used for arrangement of the cooling nozzles which would provide the required cooling conditions under control.

Table 1. The main constructive dimensions of SCZ

Zone	*r*		*R*		Length, [m]
	Number collectors	Number nozzles	Number collectors	Number nozzles	
I	2	8	2	8	0,2
II	3	3 × 6	3	3 × 6	1,47
III	2	2 × 5	2	2 × 5	1,42
IV	2	2 × 4	2	2 × 5	1,2
V	1	8	1	2 × 4	1,75
VI	1	8	1	2 × 4	2,67

Equation (1) can be solved numerically by finite difference method [18]. It is approximated by finite difference replacements for the derivatives in order to calculate values of temperature, $T_{i;j}$, at time $\tau_n = n\Delta\tau$ on a fixed grid in the (x-y) plane. Using the explicit finite difference method, the new temperature $T(i, j)^{\tau+\Delta\tau}$ at time $(\tau + \Delta\tau)$ can be calculated from the temperature of previous time step, (τ). For accounting the effective heat capacity an additional iterative procedure described in [19] was developed.

The conditions of computation and used thermophysical data are given in tab. 2.

Table 2. Conditions of continuous casting and computation

Parameter	Value
A half of slabs width S_1, [m]	0.75
A half of slabs thickness S_2, [m]	0.11
Length of mould, [m]	1.1
Superheat of the melt ΔT, [K]	5-15
Heat flux in the mould q, [Wm^{-2}]	Exp(14.2162 – 36.9872 τ)
Cell size $\Delta x = \Delta y$, [m]	0.005; Fo ≤ 0.25
Heat capacity of steel C, [kJkg^{-1}] [20]	0.75
Enthalpies of transformation L, [kJkg^{-1}] [20]	272
Thermal conductivity λ, [Wm^{-1}K^{-1}] [21]	$421.07 - 1.0816\,T + 9.59655\ 10^{-4}T^2 - 2.7376\cdot10^{-7}\,T^3$

Preliminary computations were performed to verify the adequacy of the mathematical model. A comparison between the theoretically predicted and the experimentally measured shell thickness [22] is shown on fig. 3. Figure 3 shows a good agreement between theory and experiment and demonstrates the suitability of the developed mathematical model. Other verification procedures and developed mathematical model are presented in details in [12, 17, 23]

For research in the cooling processes and the temperature field on the surface and inside the bulk of the metal during continuous casting of half-finished products for flat products, a numerical implementation of the mathematical model describing the cooling and solidification processes and permitting determining of the cooling system parameters guaranteeing production of high-quality blocks, is developed. Therefore, optimization procedures, by means of imposed constraints with respect to the strained condition of the shell, cooling rate, liquid phase depth of penetration and through re-heating of the block surface from the secondary-cooling zone outlet were developed. The values of heat transfer coefficients in particular sections SCZ have been determined (fig. 4). They satisfy the required limitations in connection with the cooling rate (V_c < 80 °C/m) on the block surface and the warm-up temperature (ΔT < 50 °C) after the block leaves SCZ.

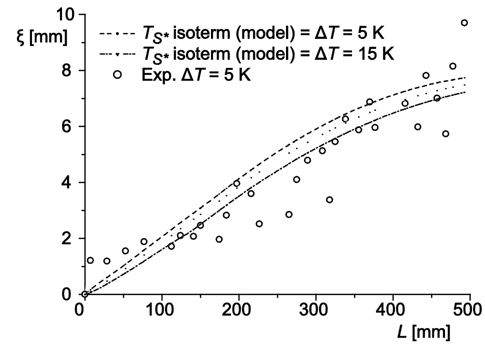

Figure 3. Comparison between the theoretically predicted and the experimentally measured shell thickness [22]

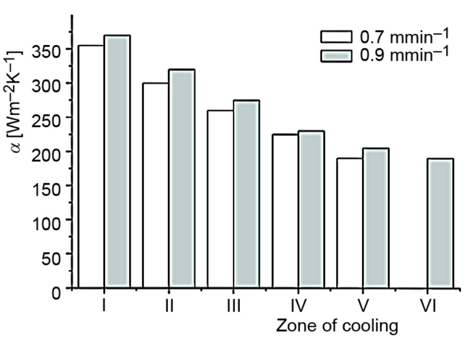

Figure 4. Values of heat transfer coefficients in particular zones of SCZ

The obtained results for the temperature distribution in one half of the block cross-section for different speeds of casting are presented in fig. 5.

The average temperature T_{cc} of the metal and heat contents Q_{cc} of the outlet of MCSC depending on the rate of drawing are outlined in fig. 6.

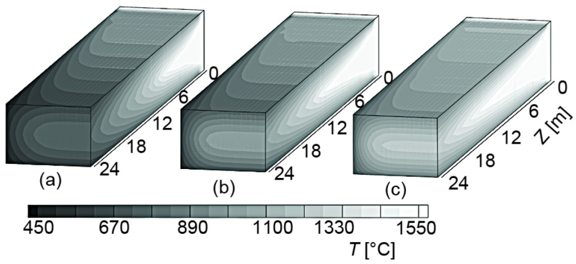

Figure 5. Temperature fields in the one half of block volume for casting speed; (a) –0.5 m per min, (b) –0.7 m per min, (c) –0.9 m per min

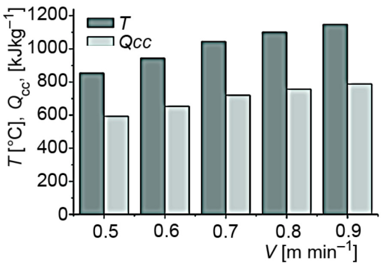

Figure 6. Average temperature of the metal and heat contents of the outlet of MCSC depending on the casting speed

The obtained results are used as initial conditions in establishing the thermal condition of the blocks during their transportation and standing in the rolling shop.

In order to determine the temperature distribution inside the blocks and make an assessment of their thermal condition, a numerical implementation of the mathematical model describing the heat exchange processes during standing and transportation of the metal from the machine for continuous steel casting to the furnaces for pre-deformation heating, was developed.

The mathematical model indicates the thermal and temperature condition at each individual moment of time throughout the transport operations. Two options were envisaged as possibilities for standing of the blocks in the rolling shop: in the open air in the shop and in a thermal box.

The research using the computing algorithm created for this study was carried out taking into account the temperature fields on cross section of the blocks of the outlet of MCSC. After the numerical simulations involving the temperature condition of the blocks, their heat contents and residual heat depending on the manner of storage in the rolling shop were obtained. The change of the average temperature of the 1st, Tbl (1), 5th, Tbl (5), and 8th, Tbl (8) block and the average temperature of the whole stack (Tbl. av.) depending on time in the case of storage in the rolling shop in an open-air stack for the temperature field at the outlet of MCSC, typical of a casting rate $V = 0.8$ m per min are presented in fig. 7(a).

In the rolling shop, the blocks which will not be immediately charged in the reheating furnaces can be stacked in thermally insulated boxes instead of staying in the open air. In this case the thermal losses are minimized and their charging temperature in the furnaces is higher. The results for the temperature distribution in blocks standing in thermally insulated box are presented in fig. 7(b).

The temperature distribution for one half of the cross section of the blocks, stacked for 90 minutes and 150 minutes from the end of casting is presented in fig. 8, where stack has just been rearranged at 150 minutes in the rolling shop storage, which explains the high irregularity of the temperature field.

The variation of the average stack temperature during transport for both options of standing in the rolling shop and the maximum temperature difference in the stack is presented in fig. 9. The figure shows that the average stack temperature after 330 minutes standing in a thermally insulated box is approximately 200 °C higher than that after standing in the open air which is 195 kJ/kg higher heat contents.

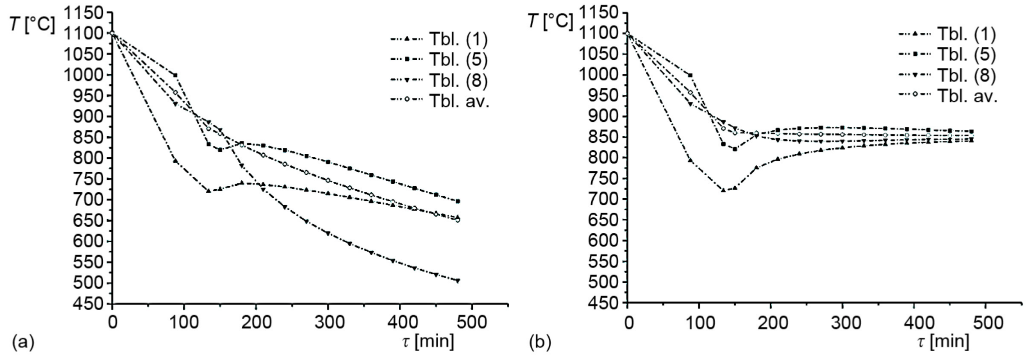

Figure 7. Temperature distribution in blocks standing in: (a) open-air stack, (b) thermally insulated box

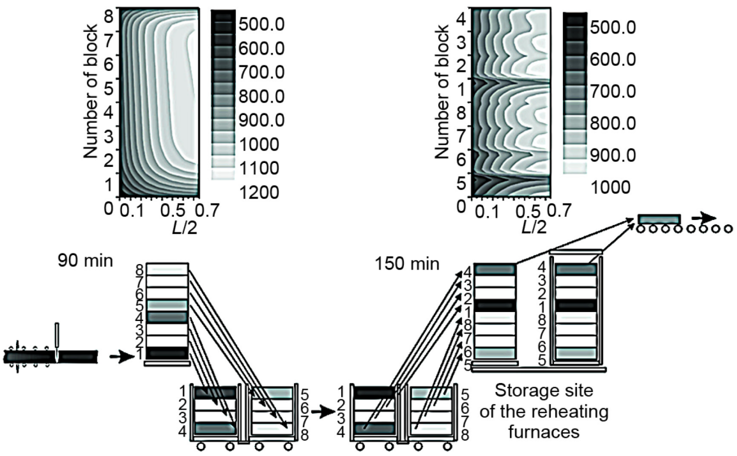

Figure 8. Temperature distribution for one half of the cross section of the blocks, stacked for 90 minutes and 150 minutes from the end of casting

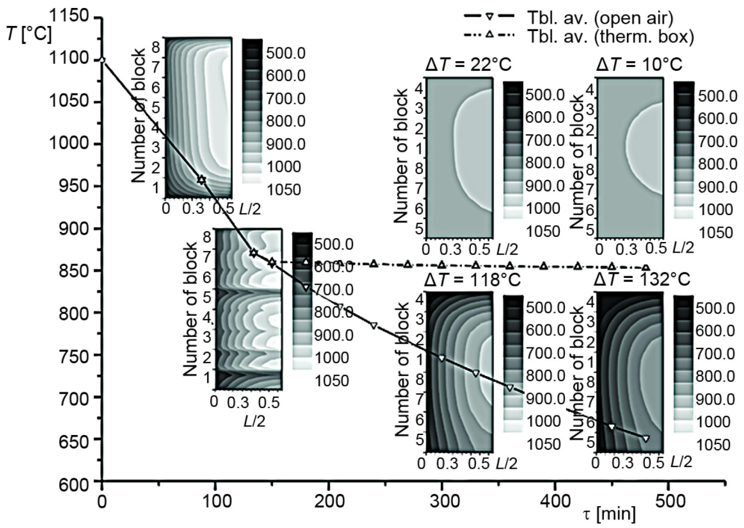

Figure 9. Variation of the average stack temperature during transport and the maximum temperature difference in the stack

The results obtained for the temperature field and thermal condition of the blocks during their transportation and standing in the rolling shop can be viewed as initial conditions in determining the optimal modes of pre-deformation heating.

Moreover, in tab. 3 is summarized the case of standing of the blocks in an open-air stack for three different metal temperatures at the outlet from the continuous casting machine, corresponding to casting rates 0.7 mpermin^{-1}, 0.8 mpermin^{-1}, and 0.9 mpermin^{-1}. From tab. 3 one can notice that, depending on the casting speed and the respective mean metal temperature at the outlet of the machine, 150 minutes after the end of casting, the average heat contents of the stack is 43-46% of the initial heat contents, after 330 minutes it is within the limits of 33-37%, and after 480 minutes – 28 to 30%.

Table 3. Average temperature (T_{cc}) of the metal on the exit of MCSC, average temperature (T) of the metal during transport operations, and heat contents (Q_{cc}) in the case of standing of the blocks in an open-air stack

	Time after the end of casting, [minutes]								
$\tau = 0$	$\tau = 150$			$\tau = 330$			$\tau = 480$		
T_{cc}, [°C]	T, [°C]	Q_{cc}, [kJkg^{-1}]	I_{cc}, [%]	T, [°C]	Q_{cc}, [kJkg^{-1}]	I_{cc}, [%]	T, [°C]	Q_{cc}, [kJkg^{-1}]	I_{cc}, [%]
1050	830	577	43	707	442	33	633	380	28
1100	860	590	45	728	466	35	651	394	29
1150	890	618	46	748	490	37	667	407	30

Similar results, obtained also for the option of the stack standing in a thermal box, are presented in tab. 4. From tab. 4 one can see that 150 minutes after the end of casting the heat contents is similar to that in the case of an open-air stack, because by that moment the blocks have been transported to the rolling shop and that is the moment immediately after they have been unloaded and stacked there. The average heat contents of the blocks 330 minutes after the end of casting is 43-46% and the cooling is negligible up to 480 minutes after casting.

Table 4. Average temperature (T_{cc}) of the metal and heat contents (Q_{cc}) in the case of standing in a thermal insulated box

	Time after the end of casting, [minutes]								
$\tau = 0$	$\tau = 150$			$\tau = 330$			$\tau = 480$		
T_{cc}, [°C]	T, [°C]	Q_{cc}, [kJkg^{-1}]	I_{cc}, [%]	T, [°C]	Q_{cc}, [kJkg^{-1}]	I_{cc}, [%]	T, [°C]	Q_{cc}, [kJkg^{-1}]	I_{cc}, [%]
1050	830	577	43	829	576	43	827	574	43
1100	860	590	45	855	594	45	848	589	44
1150	890	618	46	880	612	46	878	610	46

For successful implementation of the *hot charging* method it is necessary to establish the quantitative relationships between the temperature of the charged metal, rate of rolling, mean productivity, fuel consumption, and quantity of dross, respectively. Based on current research, a quantitative assessment for efficiency of operation technology development of the hot charged blocks can be made.

For this purpose, a computing algorithm permitting determination of the thermal and temperature modes of metal heating was developed and implemented. This algorithm is based on:

– location of the individual blocks in the working space of the furnace,
– their temperature condition,
– chemical composition of the metal,
– dimensions, and
– time in which they shall leave the furnace.

The computing algorithm allowed us to determine the metal temperature field in the process of heating. Its numerical implementation allowed determining the optimal modes of heating under the respective initial conditions. On the basis of the computed energy consumption, with guaranteed quality of heating, an evaluation can be made considering the efficiency of implementation of this technology. The quantified variables are:
– gas temperatures over the heating zones,
– relative heat consumption,
– fuel consumption in the heating zones,
– temperature of the heat insulation in the heating zones,
– mean metal temperatures in certain positions in the furnace, and
– the temperature field in the blocks.

The obtained temperature profile along the furnace walls in the top (Tw_tz), bottom (Tw_bz) heated zone, and the centre (Tm_c) of the block for a productivity of 150 th^{-1} and mean temperature of charging of metal 800 °C in the furnace are presented in fig. 10. The furnace dimensions are 29 × 8.7 m and it consists of four zones: continuous, two high-temperature heating zones, and an equalizing zone, where heating is unilateral. The block dimensions are 0.22 m × 1.5 m × 7.5 m.

The results obtained for energy consumption (Q_f) for a heating productivity of 150 th^{-1} in implementation of hot charging of the blocks depending on temperature of charging (T_{ch}) are presented in fig. 11. The results analysis shows that energy consumption at 150 th^{-1} productivity can be reduced from 1985 kJ/kg at 20 °C to 1568 kJ/kg for 400 °C, and 973 kJ/kg for 800 °C, which represents 21% and 51% energy saving, respectively. Similar values are obtained also for a productivity of 130 th^{-1}. Application of hot charging at low furnace productivities of 70 th^{-1} goes to energy savings up to 33%.

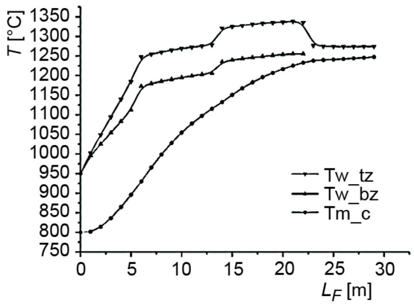

Figure 10. Temperature profile along the furnace (L_F) for a productivity of 150 th^{-1}

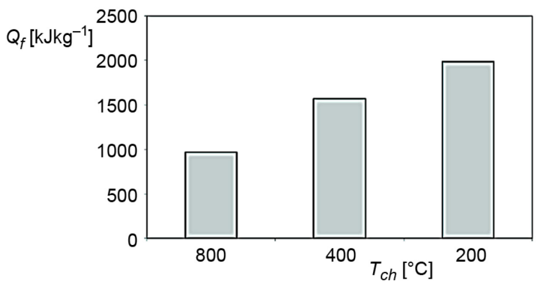

Figure 11. Energy consumption for re-heating in implementation of hot charging technology

The computing algorithm developed by means of the created mathematical model of metal heating in the furnaces for pre-deformation heating at preset hourly productivity of the rolling mill, assortment, temperatures of charging and of extraction of the heated metal and regulated stands of the mill permits to compute the furnace temperature and heat transfer modes ensuring heating with the minimum energy consumption. Also, it allows us to make an assessment of the operating consumptions and required capital investments. The obtained results show unambiguously the benefits of organizing hot charging. Moreover, the development of a system for matching of the production operations between the continuous casting machine, the heating furnaces and the roller mill and process control guarantees quality products with minimum energy consumption.

Moreover, this technique needs integration of the developed mathematical models with their computing algorithms into one common algorithm which, in essence, represents the control technology of the continuous casting – rolling mill complex, dynamically matching the operation of the individual units with the actual production conditions in on-line mode (fig. 12).

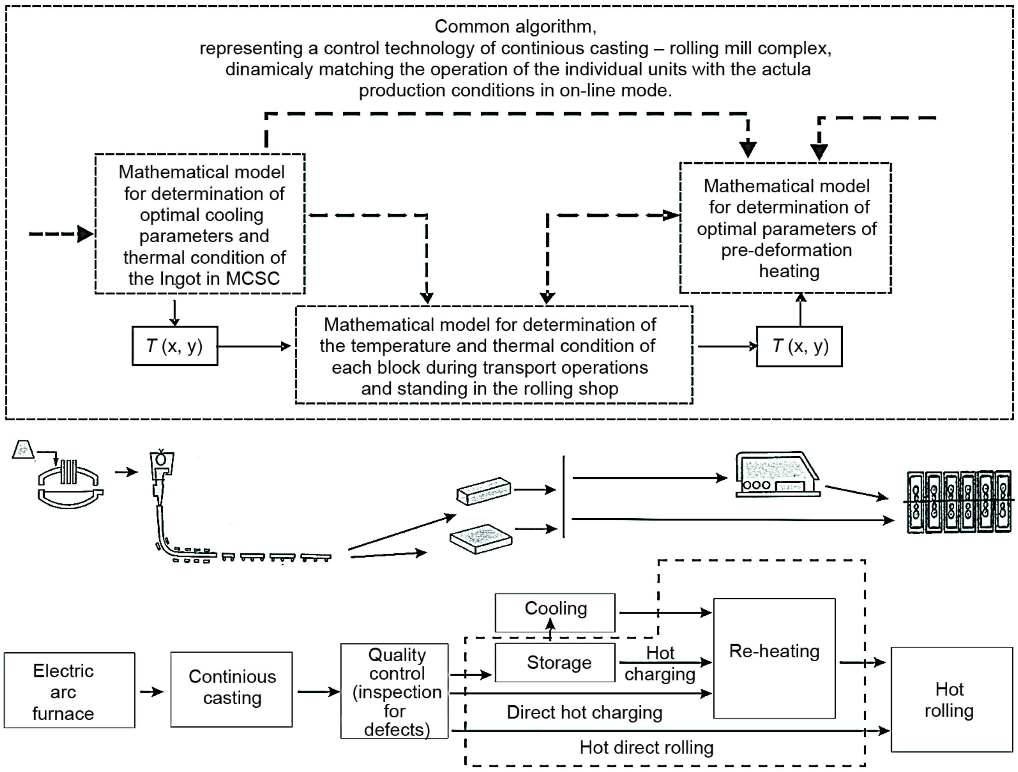

Figure 12. Common algorithm, representing a control technology of continuous casting – rolling mill complex

Therefore, our complex computing algorithm includes:

- determining of optimal cooling parameters, the temperature and thermal condition of the block in MCSC,
- determining of the temperature and thermal condition of each block during transport operations and standing in the rolling shop depending on its particular location and manner of storage till the start of pre-deformation heating, and
- determining the optimal parameters of pre-deformation heating depending on the temperature of charging, productivity and production schedule of the mill and organization of the operation of the whole complex, taking into account the expected stands and the actual and required productivity of the individual units integrated in the general technological cycle.

Thus, the developed algorithm can be used as a part of a tracking system for the blocks and to analyze their thermal condition at each moment in order to optimize the overall technological process in matching of the operations of the MCSC with those of the roller mills.

Conclusions

For process heat transfer research and to determine the optimal parameters of the technological process of production of flat products in ferrous metallurgy, complex mathematical models are developed, taking into account the options of standing before heating and a mathematical model of metal heating in the re-heating furnaces needed. These models include solidification and cooling of the metal in machine for continuous steel casting, cooling of the blocks during their transportation to the rolling shop.

For efficient implementation of such technology on the basis of the individual mathematical models, one common algorithm, representing a control technology of continuous casting – rolling mill complex, dynamically matching the operation of the individual units with the actual production conditions in on-line mode, was acquired.

The numerical results analysis, considering the original developed algorithm, shows that the implementation of hot charging technology can significantly reduce the energy consumption. The lowest percentage was 21% and the highest registered was 51%.

The developed algorithm can be used as part of a system for tracking the blocks and analyzing of their thermal condition at each moment for the purpose of optimizing the operation of the units of the overall technological process in matching the operations of the MCSC with those of the roller mills.

Nomenclature

C, C_{eff} – specific heat and effective specific heat, respectively, [kJkg^{-1}K^{-1}]
C_{L}, C_s – specific heat of solid and liquid metal, respectively, [kJ, kg^{-1}K^{-1}]
C_S* – the current solid concentration, [wt.%]
C_0 – initial solute concentration, [wt.%]
Fo – Fourier number
h_{C} – convective heat transfer coefficient, [Wm^{-2}K^{-1}]
h_m – heat transfer coefficient, [Wm^{-2}K^{-1}]
h_{tcc} – thermal contact conductance, [Wm^{-2}K^{-1}]
k – equilibrium redistribution coefficient
L_s – latent heat, [Wm^{-2}K^{-1}]
q_1, q_2 – thermal flux on x- and y-direction, respectively, [Wm^{-2}]
S_1, S_2 – half of the width and depth of the blocks, [m]
T_c – initial temperature of casting metal, [K]
T_{cc} – temperature of the metal cross section at the output of continuous casting machine, [K]
T_{L}, T_{S} – temperature of the liquid and solid metal, respectively, [K]
T_{M} – metal surface temperature, [K]
T_{M1}, T_{M2} – the temperatures of the bottom and top surface of the blocks, respectively [K]
T_{W} – cooling water temperature, [K]
V_c – cooling rate, [°Cm^{-1}]
z – length on axis z, [m]

Greek symbols

ε_{M} – surface emissivities of the metal
λ, λ_{eff} – heat conductivity and effective heat conductivity of the alloy, respectively, [Wm^{-1}K^{-1}]
ρ, ρ_{eff} – density and effective density of the metal, respectively, [kgm^{-1}]
ρ_{S}, ρ_{L} – density of the solid and liquid metal, respectively, [kgm^{-1}]
σ_0 – Stephan-Boltzmann constant, [Wm^{-2}K^{-4}]
ψ_{S} – fraction of the solidified metal
Ω – parameter expressing the degree of back diffusion of solute element

Subscripts

S – solid
L – liquid

Acronyms

CCM – continuous casting machine
MCSC – machine for continuous steel casting
SCZ – secondary cooling zone

Acknowledgments

This paper has been produced with the financial assistance of the European Social Fund, project number BG051PO001-3.3.06-0014. The author is responsible for the content of this material, and under no circumstances can be considered as an official position of the European Union and the Ministry of Education and Science of Bulgaria.

References

[1] Storck, J., Lindberg, B., A Cost Model for the Effect of Setup Time Reduction in Stainless Steel Strip Production, *Proceedings,* 1st Swedish Production Symposium, Gothenburg, Sweden, 2007, pp. 1-8
[2] Shamanian, M., Najafizaden, A., Hot Charge of Continuously Cast Slabs in Reheating Furnaces, *ISIJ International, 44* (2004), 1, pp. 35-37
[3] Ortner, A., Fitzel, H., Energy Requirements and Energy Potentials by Introduction of New Technologies from Liquid Steel to Hot Rolled Strip or Long Products, *Proceedings,* International Conference „The Efficient Use of Energy in Metallurgy",Varna, Bulgaria, 1999, pp. 13-19
[4] Tang, L., *et al.*, A Review of Planning and Scheduling Systems and Methods for Integrated Steel Production, *European Journal of Operational Research*, *133* (2001), 1, pp.11-20
[5] Ivanova, M., *Possibilities for Increasing the Energy Efficiency of Furnaces in Extractive Ferrous Metallurgy,* Ph. D. thesis, UCTM-Sofia, Sofia, 2012
[6] Laki, R., *et al.*, Prediction of Dendrite Arm Spacing and D-Ferrite Fractions in Continuously Cast Stainless Steel Slabs, *Ironmaking and Steelmaking, 4* (1985), pp. 163-170
[7] Wang, H., *et al.*, Mathematical Heat Transfer Model Research for the Improvement of Continuous Casing Slab Temperature, *ISIJ International, 45* (2005), 9, pp. 1291-1296
[8] Alizadeh, M., *et al.*, Mathematical Modeling of Heat Transfer for Steel Continuous Casting Process, *International Journal of ISSI*, *3* (2006), 2, pp. 7-16
[9] Santos, J., *et al.*, The Use of Artificial Intelligence Technique for the Optimisation of Process Parameters Used in the Continuous Casting of Steel, *Applied Mathematical Modelling*, *26* (2002), 11, pp. 1077-1092
[10] Emelyanov, V., *Heat Engineering of Continuous Casting Machines*, Metallurgy, Moscow, 1988
[11] Camisani, F., *et al.*, Speed Disturbance Compensation in the Secondary Cooling Zone in Continuous Casting, *ISIJ International*, *40* (2000), 5, pp. 469-477
[12] Mihailov, E., Petkov, V., Heat Transfer in Process Integration: Modeling, *Advances in Industrial Heat Transfer* (Ed. A. A. Minea)*,* Taylor & Francis Group, Abington, UK, 2012, pp. 91-134
[13] Patankar, S., *Numerical Heat Transfer and Fluid Flow*, Hemisphere, New York, USA, 1980
[14] Mohammed, S., The Investigation of Furnace Operating Characteristics Using the Long Furnace Model, *Leonardo Journal of Sciences*, *10* (2007), 6, pp. 55-66
[15] Marino, P., *et al.*, Numerical Model of Steel Slab Reheating in Pusher Furnaces, *Latin American Applied Research*, *32* (2002), 3, pp. 257-261
[16] Han, S., *et al.*, A Numerical Analysis of Slab Heating Characteristics in a Walking Beam Type Reheating Furnace, *International Journal of Heat and Mass Transfer, 53* (2010), 19-20, pp. 3855-3861
[17] Petkov, V., Mihailov, E., The Mathematical Simulation of Continuous Casting of Steel, *Proceedings,* 8th International Metallurgy and Materials Congress*,* Vol. 1, Istanbul, Turkey, 1995, pp. 289-294
[18] Kreit, F., Black, W., *Basic Heat Transfer*, Harper and Row, New York, USA, 1980
[19] Marchenko, I., *Semi-Continuous Casting of Steel*, Metallurgy, Moscow, 1986
[20] Kobayashi, S., Mathematical Analysis of Solute Redistribution during Solidification Based on a Columnar Dendrite Model, *Transactions ISIJ, 28* (1988), 9, pp. 728-735
[21] Efimov, V., *Casting and Solidification of Steel*, Metallurgy, Moscow, 1976
[22] Cline, T., *et al.,* The Use of Empirical, Analytical and Numerical Models to Describe Solidification of Steel During Continuous Casting, *Journal of Metals, 34* (1982), 2, pp. 34-39
[23] Mihailov, E., Petkov, V., Cooling Parameters and Heat Quantity of the Metal during Continuous Casting of Blooms, *International Review of Mechanical Engineering, 4* (2010), 2, pp. 176-184

Paper submitted: February 18, 2014
Paper revised: May 1, 2014
Paper accepted: June 11, 2014