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THE INFLUENCE OF THE CHEMICAL COMPOSITION OF STEELS ON THE NUMERICAL SIMULATION OF A CONTINUOUSLY CAST SLAB

VPLIV KEMIČNE SESTAVE JEKEL NA NUMERIČNO SIMULACIJO KONTINUIRNO LITE PLOŠČE

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The chemical composition of steels has a significant influence on the actual concasting process, and on the accuracy of its numerical simulation and optimization. The chemical composition of steel affects the thermophysical properties (heat conductivity, specific heat capacity and density in the solid and liquid states) and often requires more time than the actual numerical calculation of the temperature fields of a continuously cast steel slab. Therefore, an analytical study of these thermophysical properties was conducted. The order of importance within the actual process and the accuracy of the simulation were also determined. The order of significance of the chemical composition on the thermophysical properties was determined with respect to the metallurgical length. The analysis was performed by means of a so-called calculation experiment, i.e., by means of the original numerical continuously cast model developed by the authors of this paper. It is convenient to conduct such an analysis in order to facilitate the simulation of each individual case of continuously cast steel, thus enhancing the process of optimization.

Keywords: concast slabs, chemical composition, numerical model, solidification

Kemična sestava jekla ima pomemben vpliv na dejansko kontinuirno lije ter na točnost numerične simulacije in optimizacije. Kemična sestava jekla vpliva na termične lastnosti (na toplotno prevodnost, specifično toploto in gostoto v trdnem in tekočem stanju) pogosto zahteva več časa kot dejansko numerični izračun temperaturnega polja kontinuirno lite jeklene plošče. Zato je bila izvedena analitična študija teh termofizikalnih lastnosti. Zaporedja pomembnosti samega procesa in natančnost simulacije so bili tudi določeni. Vrstni red pomena kemijske sestave na termofizikalne lastnosti je bil določen glede na metalurško dolžino. Analiza je bila izvedena s tako imenovanim poskusom izračuna, tj. z uporabo prvotnega numerično kontinuirnega litega modela avtorjev tega članka. To je priročno za izvajanje teh analiz, da bi se olajšala simulacija za vsak posamezni primer kontinuirnega litja, kar spodbujaja proces optimizacije.

Ključne besede: kontinuirno uliti drogovi, nihajoče oznake, numerični model, strjevanje

1 INTRODUCTION

The production of steels, alloys and metallurgical products in general is constantly developing. Materials with high utility parameters are more in demand and traditional production is being replaced by better quality steel. More and more sophisticated aggregates using more sophisticated technological procedures are being implemented. In order to maintain competitiveness, diversify production and expand into other markets, it is necessary to monitor the technological development.

In the case of concasting, it is not possible to fulfil these requirements without the application of models of all caster processes dependent on thermal-mechanical relationships. These models can be applied both off-line and on-line. An off-line model is the one where the calculations typically take a longer time than the actual casting process. An on-line model runs in real time – taking the data directly from the operation – and its calculation runs in real time.

These models will support the design of new and the redesign of old machines, they will facilitate the identification and quantification of any potential defects and the optimization of the various operational conditions in order to increase the productivity and minimize the occurrence of defects. The process of the solidification of concast steel is influenced by many factors and conditions, among which are the following:

- Complete turbulent transient flow within a comprehensive geometry (input jet and liquid metal in the slab).
- Thermodynamic reactions between the casting powder and the solidifying slab.
- Heat transfer between the liquid and solid powder on the surface of the slab.
- Dynamic movement of the liquid steel inside the mould on the liquid-phase–mushy-zone interface, including the influence of gravity, oscillations and the casting speed.
- Heat transfer in a superheated melt considering the turbulent flow.
- Transition (mixture) composition of the steel during the change of class.

- Heat and mechanical interaction in the area of the meniscus between the solidifying meniscus, the solid powder and the liquid steel.
- Heat transfer from the surface of the solidified shell into the space between the shell and the working surface of the mould (including the layers of the casting powder and the air gap).
- Mass transfer of the powder during its vertical movement through the gap between the shell and the mould.
- Contact of the solidified slab with the mould and support rollers.
- The formation of crystals inside the melt.
- The process of micro-segregation and macro-segregation.
- The occurrence of shrinkages as a result of temperature contraction of the steel and the initialization of internal stresses.
- The occurrence of stress and strain in the solidified shell as a result of external influences such as the friction inside the mould, bulging between rollers, rolling, temperature stress and strain.
- The occurrence of cracks as a result of internal stresses.
- The flow of steel as a result of the electromagnetic stirring and the influence of the stirring on the temperature field and the primary structure.
- The occurrence of stress and strain as a result of unbending of the inside the segments or in the rolling mill.
- Radiation between the various surfaces.
- Cooling as a result of convection beneath the water or the water-air jets.

With respect to the complexity of the investigation into the influence of all of the above-mentioned factors, it is not possible to develop a mathematical model that would cover all of them. It is best to group them according to the three main types of influence:

- Heat and mass transfer
- Mechanical
- Structural

The primary and deciding one is the influence of heat and mass transfer because it is the temperature field that gives rise to the mechanical and structural influences. The development of a model of the temperature field (of a slab) with an interface for providing data for mechanical stress and strain models and structure models is therefore a top-priority task [1].

2 MODEL OF THE TEMPERATURE FIELD OF A SLAB

The 3D model was first designed as an off-line version and later as an on-line version so that it could work in real time. After corrections and testing, we are working towards its implementations on any caster thanks to the universal nature of the code. The numerical model takes into account the temperature field of the entire slab (from the meniscus of the level of the melt in the mould to the cutting torch) using a 3D mesh containing more than a million nodal points.

The solidification and cooling of a concast slab is a general problem of 3D transient heat and mass transfer. If the heat conduction within the heat transfer is decisive, the process is described by the Fourier-Kirchhoff equation (Equation 1). It describes the temperature field of the solidifying slab in all three of its states: at the temperatures above the liquidus (i.e., the melt), within the interval between the liquidus and solidus (i.e., in the mushy zone) and at the temperatures below the solidus (i.e., the solid state). In order to solve these it is convenient to use the explicit numerical method of finite differences. The numerical simulation of the release of latent heats of phase or structural changes is carried out by introducing the enthalpy function dependent on the temperature T, preferably in the form of enthalpy related to the unit volume H_v. The latent heats are contained here (**Figure 1**). After the automated generation of the mesh (pre-processing) ties on the entry of the thermophysical material properties of the investigated system, including their dependence on temperature – in the form of tables or using polynomials. They are namely the heat conductivity k, the specific heat capacity c and the density ρ of the cast metal.

The temperature distribution in the slabs described by the enthalpy balance equation

$$\frac{\partial \boldsymbol{H}_v}{\partial \tau} = \frac{\partial}{\partial x}\cdot\left(k\cdot\frac{\partial \boldsymbol{T}}{\partial x}\right)+\frac{\partial}{\partial y}\cdot\left(k\cdot\frac{\partial \boldsymbol{T}}{\partial y}\right)+\frac{\partial}{\partial z}\cdot\left(k\cdot\frac{\partial \boldsymbol{T}}{\partial z}\right)+ + \left(u\cdot\frac{\partial \boldsymbol{H}_v}{\partial x}+v\cdot\frac{\partial \boldsymbol{H}_v}{\partial y}+w\cdot\frac{\partial \boldsymbol{H}_v}{\partial z}\right) \tag{1}$$

This simplified equation (1), suitable for application on radial-casters with a great radius, where only the speed (of the movement of the slab) component w in the z-direction is considered, is:

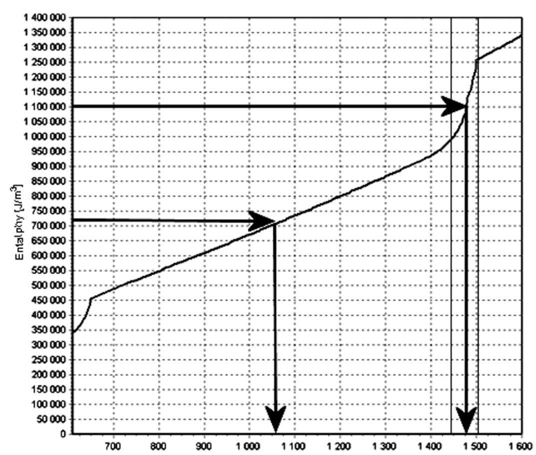

Figure 1: Enthalpy function of typical carbon steel
Slika 1: Entalpijska funkcija tipičnih ogljikovih jekel

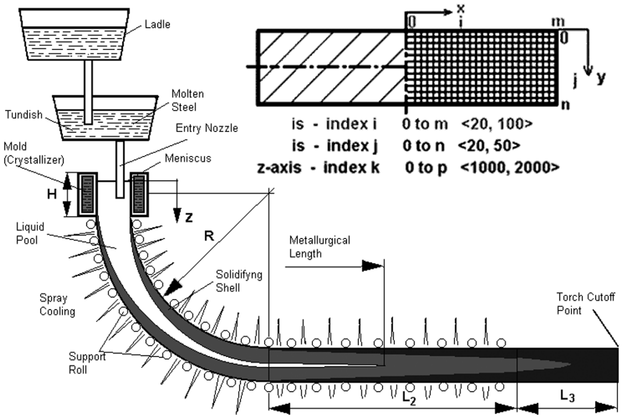

Figure 2: The mesh and definition of the coordinate system
Slika 2: Mreža in opredelitev koordinatnege sistema

$$\frac{\partial H_v}{\partial \tau} = k \cdot \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + w \cdot \frac{\partial \boldsymbol{H}_v}{\partial z} \tag{2}$$

The enthalpy H_v as a thermodynamic function of temperature must be known for each specific steel. It is dependent on the composition of the steel and on the rate of cooling. The dependence of the function H for typical carbon steel is in **Figure 1**.

Figure 2 shows that the task is symmetrical along the x-axis; it is therefore sufficient to investigate only half of the cross-section with the following boundary conditions (3a-3e)

1. $T = T_{\mathrm{cast}}$ at the meniscus (3a)
2. $-k \dfrac{\partial T}{\partial n} = 0$ at the plane of symmetry (3b)
3. $-k \dfrac{\partial T}{\partial n} = h \cdot (T_{\mathrm{surface}} - T_{\mathrm{a}})$ in the mould (3c)
4. $-k \dfrac{\partial T}{\partial n} = h \cdot (T_{\mathrm{surface}} - T_{\mathrm{a}}) + \sigma\varepsilon \cdot (T^4_{\mathrm{surface}} - T^4_{\mathrm{a}})$
   in the secondary and tertiary cooling zones (3d)
5. $-k \dfrac{\partial T}{\partial n} = q$ beneath the support rollers (3e)

The initial condition for solving is the setting of the initial temperature in individual points of the mesh. A suitable value is the highest possible temperature, i.e., the casting temperature.

Figure 3 illustrates the thermal balance of an elementary volume (general nodal point *i, j, k*) of the network.

An unknown enthalpy of the general nodal point of the slab in the next time step ($\tau + \Delta\tau$) is expressed by the explicit formula:

$$H_{v_{i,j,k}}^{(\tau+\Delta\tau)} = H_{v_{i,j,k}}^{(\tau)} + \\ +(QZ1_{i,j} + QZ_{i,j} + QY1_{i,j} + QY_{i,j} + QX1 + QX)\frac{\Delta\tau}{\Delta x \cdot \Delta y \cdot \Delta z} \tag{4}$$

The heat flow through the general nodal point (*i, j, k*) in the z-direction is described by the following equations

$$QZ_{i,j} = VZ_{i,j,k}(T^{(\tau)}_{i,j,k+1} - T^{(\tau)}_{i,j,k}) - A_z \cdot w \cdot H^{(\tau)}_{v_{i,j,k}} \tag{5}$$

Where $VZ_{i,j,k} = k \cdot A_z / \Delta z$

Figure 1 indicates how the temperature model for the calculated enthalpy in equation (4) determines the un-

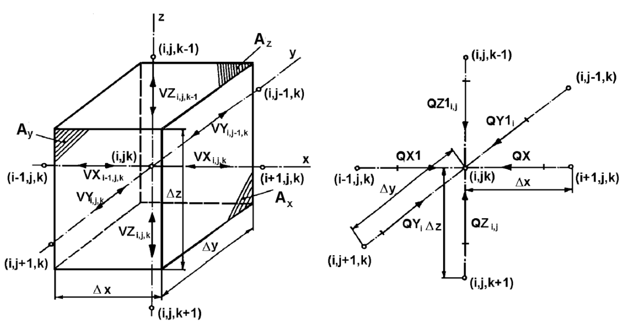

Figure 3: The thermal balance diagram for the general nodal point of the network
Slika 3: Diagram toplotnega ravnovesja v splošni točki mreže

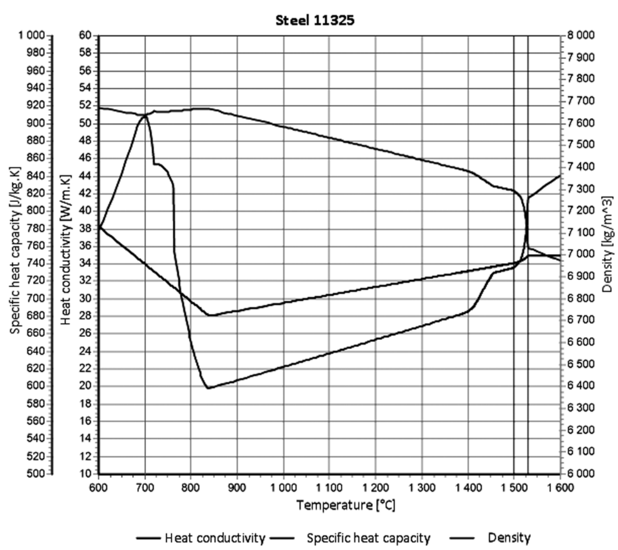

Figure 4: Thermophysical properties of the 11325 class steel from group 2 (first row of **Table 1**.)
Slika 4: Termofizikalne lastnosti jekla razreda 11325 iz skupine 2 (prva vrstica **tabele 1**)

Table 1: Selected classes of steel with their compositions used for calculation
Tabela 1: Izbrani razredi jekel in njihove sestave, *w*/%

Class	Group	Ceq	C	Mn	Si	P	S	Cu	Ni	Cr	Mo	V	Ti	Al	Nb	Tsol	Tliq
11325	2	0.067	0.050	0.225	0.025	0.010	0.010	0.150	0.150	0.150	0.040	0.050	0.0025	0.045	0.030	1499.8	1529.8
21026	5	0.235	0.150	1.075	0.300	0.0175	0.010	0.150	0.200	0.100	0.040	0.045	0.001	0.040	0.015	1451.4	1514.2
31087	3	0.275	0.190	1.450	0.200	0.015	0.010	0.100	0.150	0.100	0.040	0.010	0.001	0.040	0.030	1438.7	1510.6
11500	4	0.326	0.270	0.550	0.275	0.015	0.010	0.150	0.150	0.125	0.040	0.050	0.025	0.040	0.030	1423.2	1507.4
13180	6	0.826	0.75	1.050	0.250	0.0175	0.010	0.125	0.200	0.150	0.050	0.100	0.050	0.040	0.025	1322.7	1467.7

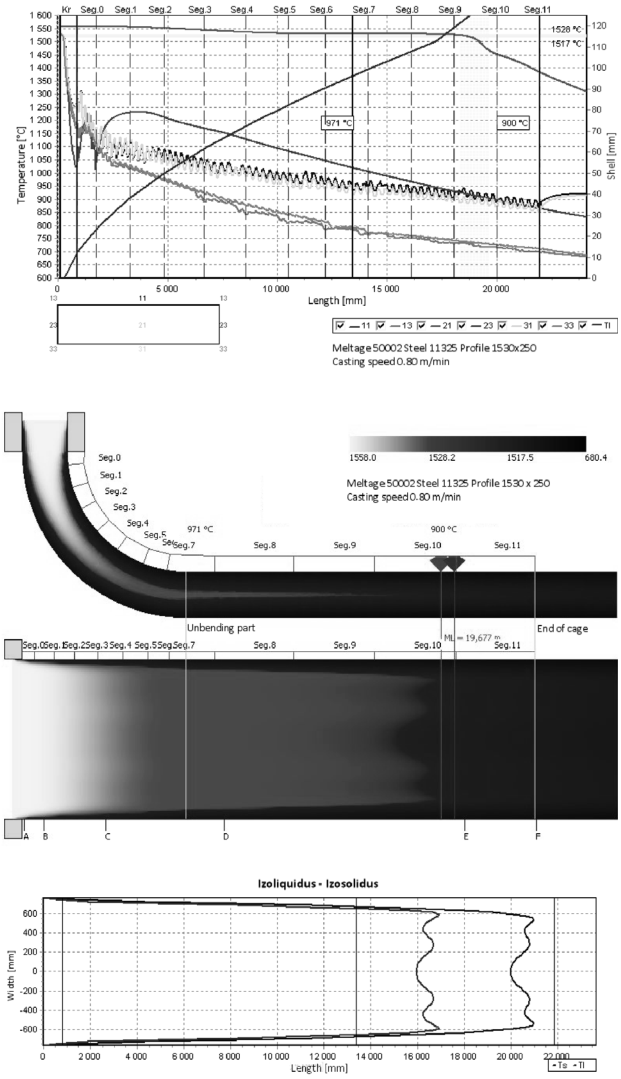

Figure 5: Temperature field of the 11325 class steel slab
Slika 5: Temperaturno polje jekla razreda 11325

known temperature. The enthalpy function is not known as an analytical function but as a set of table values, and therefore the inverse calculation of the temperature is numerically a very demanding problem. In the dynamic model where the calculation must run at least as fast as the flow of the process in real time, the method in which the interpolation values are calculated at 0.1 °C intervals even before the actual calculation was chosen. The temperature for the relevant enthalpy is then determined using modern search methods in the table.

3 THE EFFECT OF THE CHEMICAL COMPOSITION ON THE RESULTANT TEMPERATURE FIELD

A real concasting operation casts up to several hundred classes of steel. It would therefore be difficult to set the concasting and other relevant technological parameters for all of them. That is why steels are subdivided into groups, mostly according to their carbon content, preferably according to the so-called equivalent carbon content, given by:

$$C_{eq} = C - 0.1Si + 0.04Mn - 0.04Cr + 0.1Ni - 0.1Mo \quad (6)$$

A single class of steel was selected from each group for the analyses below. **Table 1** contains the recommended compositions of these steels, together with the temperatures of the liquidus and solidus. **Figure 4** illustrates an example of the dependence of the thermophysical properties on the temperature for the 11325 class steel [2]. **Figure 5** presents the calculated temperature field for this class of steel. These calculations were also performed for the remaining classes [3]. In order to analyse the influence of the chemical composition on the temperature field more clearly, the other concasting parameters were selected to be identical, i.e., a casting speed of 0.8 m/min, a superheating temperature of 30 °C and the profile of the slab equal to (1530 × 250) mm, just like the flow of water through the secondary-cooling zone. In practice, a different cooling mode is selected for each different class of steel.

Figures 6 proves the main parameters of the resulting temperature field as the effect of the chemical composition of five different steels.

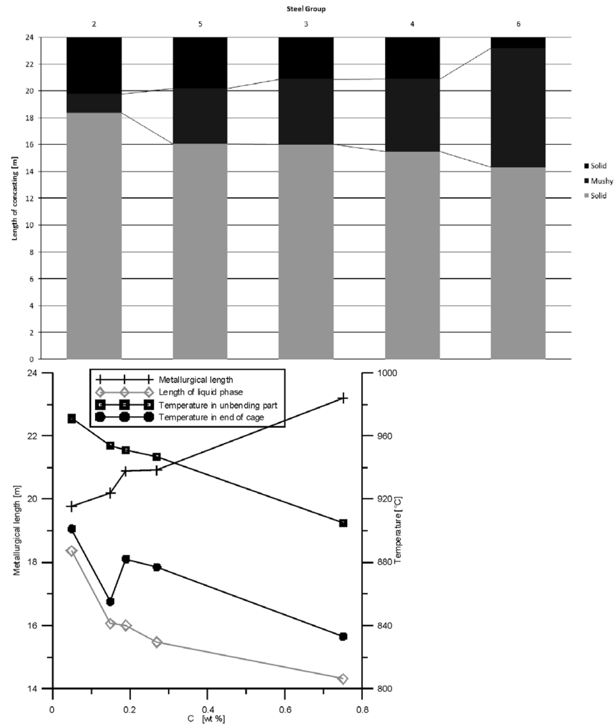

Figure 6: Comparison of the length of the liquid phase and the metallurgical length for various classes of steel
Slika 6: Primerjava dolžine tekoče faze in metalurške dolžine za različne razrede jekla

4 CONCLUSIONS

This paper introduces a 3D numerical model of the temperature field (for the concasting of steel) in the form of in-house software and has been implemented in the operations of EVRAZ VITKOVICE STEEL. The model includes the main thermodynamic transfer phenomena during the solidification of concasting. The presented model is a valuable computational tool and an accurate simulator for investigating transient phenomena in slab-caster operations, and for developing control methods, the choice of an optimum casting strategy for steel with different chemical compositions.

NOMENCLATURE

A	area	[m²]
c	specific heat capacity	[J/(kg K)]
w(Ceq)	equivalent carbon content	%
w(C)	mass composition of carbon	%
h	heat-transfer coefficient	[W/(m² K)]
H_v	volume enthalpy	[J/m³]
k	heat conductivity	[W/(m K)]
L_{LIQ}	length of the liquid phase	[m]
L_{MET}	metallurgical length	[m]
T	temperature	[K]
T_a	ambient temperature	[K]
T_{cast}	melt temperature	[°C]
$T_{surface}$	temperature in unbending part	[°C]
$T_{unbending}$	temperature in unbending part	[°C]
T_{end}	temperature in end of cage	[°C]
q	specific heat flow	[W/m²]
QX, QY, QZ	heat flows	[W]
x, y, z	axes in given direction	[m]
u, v, w	casting speed in given direction	[m/s]
VX, VY, VZ	heat conductivity	[W/K]
ρ	density	[kg/m³]
σ	Stefan-Bolzmann constant	[W/(m² K⁴)]
ε	emissivity	[-]
τ	time	[s]

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