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Recenzované vědecké články

Numerical Off-line Model of Temperature Field of a Continuously Cast Billet and its Preparation

Numerický off-line model teplotního pole plynule odlévaného sochoru a jeho příprava

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The paper is concerned with fundamental analytical and empirical knowledge about the solidification of continuously cast steel billets having a square cross-section. Solidification and cooling of this billet and the heating of the mould is a very complicated problem of transient heat and mass transfer. The solving of such a problem is impossible without numerical model of the temperature field, not only of the concasting itself, while it is being processed through the caster but of the mould as well. An original 3-D numerical off-line model of the temperature field of a billet has been developer and presented there. The model is based on an explicit finite difference method and it solves for a solution of the Fourier-Kirchhoff partial differential equation. The latent heat of phase changes is incorporated into the model by means of the enthalpy method. The preprocessing mainly includes a complicated definition of boundary conditions, especially in the secondary cooling zone, and the determination of thermo-physical steel properties as functions of the temperature. The dependence of input data (thermo-physical properties and boundary conditions) on the temperature in a particular location on the billet makes the problem highly nonlinear.

***Key words**: continuously cast billet; temperature field; discretization; initial and boundary conditions; thermo-physical properties; experimental measurement; simulation; numerical model; off-line and on-line version*

Článek uvádí základní analytické a empirické poznatky o procesu tuhnutí ocelového předlitku čtvercového profilu (sochoru) v zařízení pro plynulé odlévání oceli (ZPO). Předkládá dále základ originálního 3D modelu nestacionárního teplotního pole plynule litého sochoru a jeho přípravu. Vlastní model je založen na explicitní numerické metodě konečných diferencí. Řeší parciální diferenciální Fourier-Kirchhoffovu rovnici druhého řádu. Simulace vývinu skupenských tepel fázových nebo strukturních přeměn je provedena zavedením termodynamické funkce entalpie. Příprava zahrnuje především obtížnou a časově velmi náročnou definici okrajových podmínek řešení a zjištění hodnot hlavních termofyzikálních vlastností odlévaných ocelí, které jsou výrazně závislé na teplotě. Ke stanovení termofyzikálních vlastností model využívá finského modelu IDS. Jejich funkční závislost i závislost okrajových podmínek na teplotě povrchu předlitku v daném místě ZPO znamená, že numerický model musí řešit silně nelineární úlohu přenosu tepla. Komplikovaná je především definice okrajových podmínek v sekundární chladicí zóně. Na sochorovém ZPO se používá velké množství trysek s různým nastavením. Koeficienty přestupu tepla pod tryskami je proto třeba měřit na speciálním laboratorním zařízení. Posun předlitku je modelován pohybem trysky podél ocelové desky simulující povrch předlitku. Chladicí účinek trysky se posuzuje podle vyhodnoceného tepelného toku, který tryska odvádí z chlazeného povrchu. Stanovené koeficienty přestupu tepla pod tryskou skokem narůstají při dosažení tzv. Leidenfrostovy povrchové teploty. Předkládaný model má grafický vstup i výstup, automatickou tvorbu výpočtové sítě a znázornění teplotního pole ve formě izoterem, izoploch konstantní teploty a znázornění teplotní historie jakéhokoli bodu příčného řezu sochorem při jeho průchodu ZPO. Řeší teplotní pole ZPO jako celku nebo jeho vybrané části.

***Klíčová slova**: plynule litý sochor; teplotní pole; diskretizace; počáteční a okrajové podmínky; termofyzikální vlastnosti; experimentální měření; simulace; numerický model; off-line a on-line verze*

The dynamic model of solidification [1] was created at Brno University of Technology, Faculty of Mechanical Engineering and registered under the name Brno Dynamic Solidification Models (BrDSM) and under the

EU trademark 015723893. Since 2003 it was successfully integrated into the control system of the control system for continuous casting machine for slabs (CCM) at the steelworks VÍTKOVICE STEEL a.s. [2 - 5]. During the collaboration on the project of the Ministry of Industry and Trade of the Czech Republic entitled "Research, development, and introduction into the production of a dynamic model of control of technology for continuous casting of billets" for the steelworks Třinecké železárny a.s., this model was also successfully developed for the solution of the unsteady temperature field of the billet as a square blank it and was included in the control system for the billet continuous casting machine No. 2 (CCM2) in Třinecké železárny, a.s. [6]. Progress during the project solution pointed to the significant differences between the modelling of the continuous casting of slabs and billets. Therefore, a new numerical model, including a new software product, had to be developed for the billet CCM. The team of authors summarises the progress of the project solution and its main results in three articles for the Hutnické listy journal.

1. Original temperature model of billet on the radial continuous casting machine (CCM)

The presented 3D model of the unsteady temperature field of continuously cast blank for the billet CCM, with dimensions of the square profile 150 × 150 mm (Fig. 1), was first developed for a slab CCM as an off-line version [2] and then as an on-line in order to enable work in real time. This is its uniqueness, although this is a 3D model. Thanks to the universality of the code, it is possible to use it for any billet CCM after modification and tuning. Numerical model solves the temperature field of the entire continuously cast blank (from the molten steel meniscus in the mould to the flame cutting machine) on a 3D mesh with a number of nodes exceeding $2.5\cdot10^6$. Solidification and cooling of the continuously cast blank during its passage through the entire CCM is a complex problem of 3D unsteady heat and mass transfer. We assume from all types of heat transfer in the moving continuously cast blank, the decisive one is the conduction described by the Fourier-Kirchhoff partial differential equation (1) of the second order, comprising a member of the internal heat source (development of internal latent heats of phase transformation, or of structural transformations) and members describing the thermal flow of the molten steel running at flow rate w:

$$\rho \cdot c \ \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial y}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \rho \cdot c \ = \left(w_x\frac{\partial T}{\partial x} + w_y\frac{\partial T}{\partial y} + w_z\frac{\partial T}{\partial z}\right) + \dot{Q}_{\text{source}}\,, \qquad (1)$$

where ρ is the density ($kg\cdot m^{-3}$), c is specific heat capacity ($J\cdot kg^{-1}\cdot K^{-1}$), T is temperature (K), τ is time (s), k is thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$), x, y, z are Cartesian coordinates (m), w is speed of casting of steel, ($m\cdot s^{-1}$), $\dot{Q}_{\text{source}}$ is volume heat flow from inner source (latent heats of phase and structural transformations) ($W\cdot m^{-3}$). An explicit numerical method of finite differences is used for solution of the equation (1).

Fig. 2 shows the heat balance of the elementary volume representing the common node of the mesh (i, j, k).

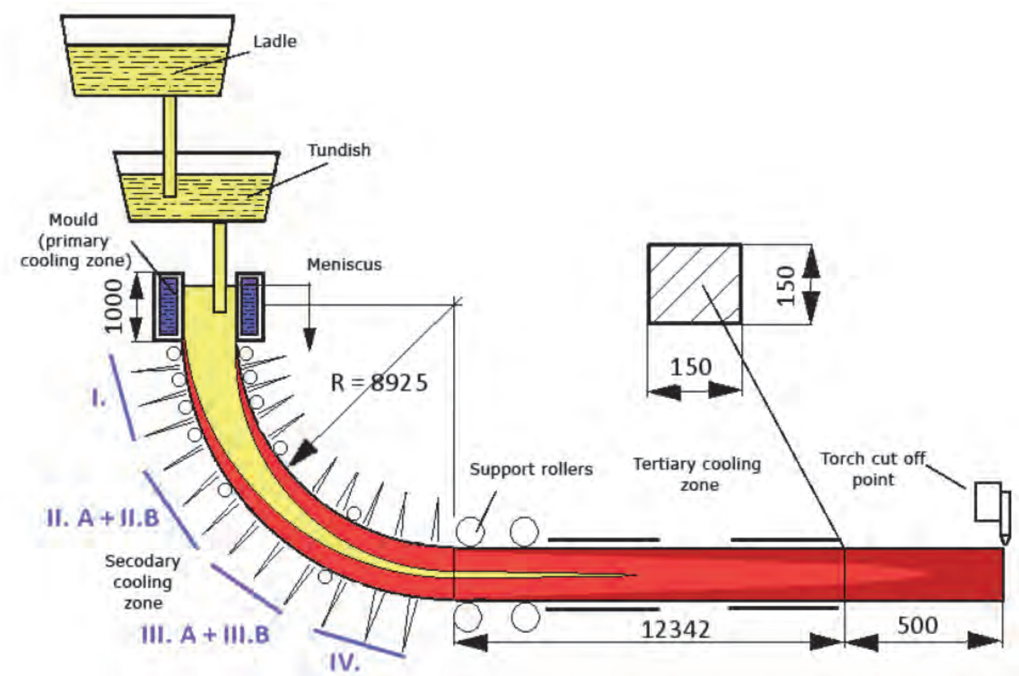

Fig. 1 Billet caster and basic concepts
Obr. 1 Sochorové ZPO a základní pojmy

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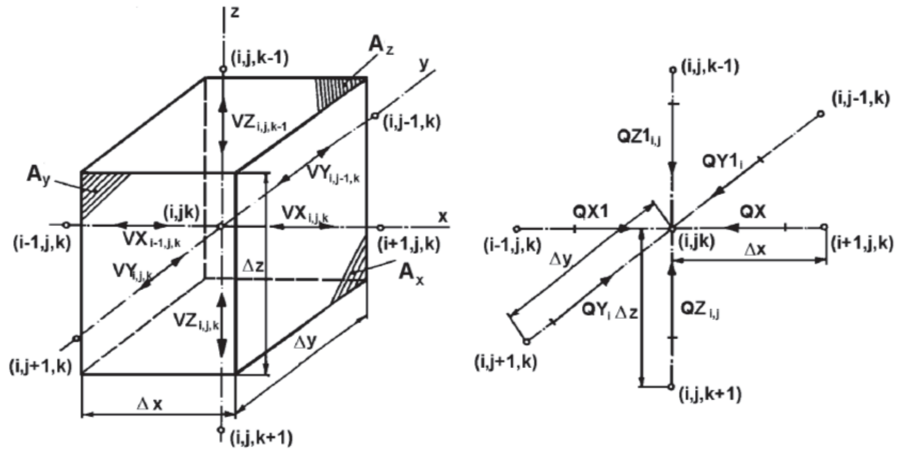

Fig. 2 Thermal balance diagram of the general nodal point of the network
Obr. 2 Schéma tepelné bilance obecného uzlu výpočtové sítě

For example, the parameter VX ($W \cdot K^{-1}$) in the x-axis direction can be written as follows:

$$VX_{i,j,k} = k_i \frac{A_x}{\Delta x} \qquad VX_{i-1,j,k} = k_{i-1} \frac{A_x}{\Delta x} \tag{2}$$

where A_x is according to Fig. 2 a plane perpendicular to the direction of the x-axis

The heat fluxes QX and $QX1$ (W) in the direction of the x-axis are

$$\begin{aligned} QX &= VX_{i,j,k} \left(T^{(\tau)}_{i+1,j,k} - T^{(\tau)}_{i,j,k} \right) \\ QX1 &= VX_{i-1,j,k} \left(T^{(\tau)}_{i-1,j,k} - T^{(\tau)}_{i,j,k} \right) \end{aligned} \tag{3}$$

The thermal balance of the elementary node of dimensions Δx, Δy, Δz are then described by the equation (4)

$$\begin{aligned} &\left(QZ1_{i,j} + QZ_{i,j} + QY1_i + QY_i + QX1 + QX \right) = \\ &\frac{\Delta x \cdot \Delta y \cdot \Delta z \cdot \rho \cdot c}{\Delta \tau} \left(T^{(\tau+\Delta\tau)}_{i,j,k} - T^{(\tau)}_{i,j,k} \right) \end{aligned} \tag{4}$$

in which the right side expresses heat accumulation (heat drop) in the node i, j, k for the time step $\Delta\tau$. The unknown temperature of the general node of the computational mesh at the next time point $(\tau + \Delta\tau)$ is therefore given by an explicit formula:

$$\begin{aligned} T^{(\tau+\Delta\tau)}_{i,j,k} &= T^{(\tau)}_{i,j,k} + (QZ1_{i,j} + QZ_{i,j} + QY1_i + \\ &QY_i + QX1 + QX\ ) = \frac{\Delta\tau}{c \cdot \rho \cdot \Delta x \cdot \Delta y \cdot \Delta z} \end{aligned} \tag{5}$$

The temperature field of the billet passing through the radial CCM with a large arc radius can be described in a simplified manner by the Fourier-Kirchhoff equation, which takes into account only the vector component of speed w_z in the direction of the billet movement through individual CCM zones. Equation (1) is reduced to this notation:

$$\begin{aligned} \rho \cdot c\ \frac{\partial T}{\partial \tau} &= \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y} \right) + \frac{\partial y}{\partial z}\left(k \frac{\partial T}{\partial z} \right) \\ &+ \rho \cdot c\ \cdot w_z \frac{\partial T}{\partial z} + \dot{Q}_{\text{source}} \end{aligned} \tag{6}$$

The equation (6) must describe the temperature field of the continuously cast blank in all its three stages: above the liquidus temperature (melt), in the interval between the liquidus and solidus temperatures (so-called mushy zone) and also below the solidus temperature (solid phase). It is therefore appropriate to introduce the thermodynamic function of the temperature-dependent specific volumetric enthalpy $H_v = c \cdot \rho \cdot T$ ($J \cdot m^{-3}$) in order to simulate latent heats of the phase and structural transformations. These are included in the enthalpy.

Thermal conductivity k, specific heat capacity c and density ρ are thermo-physical properties, which are also functions of temperature. Equation (6) is transformed into the following notation:

$$\frac{\partial H_v}{\partial \tau} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y} \right) + \frac{\partial y}{\partial z}\left(k \frac{\partial T}{\partial z} \right) + w_z \frac{\partial H_v}{\partial z} \tag{7}$$

The heat balance of the elementary node is now given by the equation (8):

$$\begin{aligned} &\left(QZ1_{i,j} + QZ_{i,j} + QY1_i + QY_i + QX1 + QX \right) = \\ &\frac{\Delta x \cdot \Delta y \cdot \Delta z}{\Delta \tau} \left(H^{(\tau+\Delta\tau)}_{v_{i,j,k}} - H^{(\tau)}_{v_{i,j,k}} \right), \end{aligned} \tag{8}$$

The heat flow $QZ_{i,j}$ must this also include an enthalpy of the inflow volume of melt per second

$$QZ_{i,j} = VZ_{i,j,k} (T^{(\tau)}_{i,j,k+1} - T^{(\tau)}_{i,j,k}) - A_z w_z H^{(\tau)}_{v_{i,j,k}} \tag{9}$$

The unknown enthalpy of the node in the next time point $(\tau + \Delta\tau)$ is given by an explicit formula of an analogous equation (5):

$$H_{v_{i,j,k}}^{(\tau+\Delta\tau)} = H_{v_{i,j,k}}^{(\tau)} + (QZ1_{i,j} + QZ_{i,j} + QY1_i + QY_i + QX1 + QX)\ \frac{\Delta\tau}{\Delta x \cdot \Delta y \cdot \Delta z} \tag{10}$$

As it is evident from the equation (10), a new value of enthalpy is calculated in each time step. For calculations of the members corresponding to the heat flows, it is also necessary to know the temperature values of the previous time step. Therefore, it is necessary for each control volume and for each time step to convert the enthalpy value to a temperature. The enthalpy function is not known as an analytical function, but as a set of tabular values, so regressive determination of temperature is a numerically challenging task. The calculation is performed quickly. Therefore, we chose a method, in which the enthalpy values were read and interpolated in the interval of 0.1 °C before the start of the calculation, i.e. before the start of casting of the new heat. Determination of the temperature for the relevant enthalpy is then during the calculation performed by modern search methods [7].

2. Spatial and temporal discretisation, initial and boundary conditions

For the solution of parabolic differential equations (1), or (10), different numerical methods are used [2]. For the solution, the method of control volumes was chosen as the most efficient way to thoroughly resolve the 3D system in real geometry with the knowledge of the already mentioned strong non-linearity of the solved equation. The principle consists in the division of the body into the so-called control volumes, which can be of different sizes and shapes according to the user's requirement concerning the mesh density, and which thus may affect the accuracy of the solution. After the division of the domain into the control volumes, a heat balance equation is compiled for each volume. Namely, the application of the basic physical energy conservation law allows continuous expansion and tuning of the model with more physical phenomena.

Fig. 3 presents a selection of the coordinate system and the diagram of the computation mesh [8]. Solution deals with the symmetrical half of the billet cross-section from the molten steel level in the mould to the flame cutting/burning machine (Figs. 1 and 3). The coordinate system is chosen so that the start is located at half the width of the billet on a small radius, x is in the width direction, y is in the height direction, and z is in the direction of casting. The advantage of this option is that all coordinates are positive, which makes it easier to prepare software processing. In the zone of billet bending, the rectangular coordinates are transformed into cylindrical ones, i.e. y is the radius and z is the angle of rotation of the billet cross section. The calculation network is generated automatically. The developed model supports network densities as shown in Fig. 3. We chose in the x-axis direction 11 nodes, in the y-axis direction 21 nodes and in the z-axis direction 1861 nodes; the element size is $7.5 \times 7.5 \times 15$ mm and the number of nodes in the network is 573 594. This calculation network allows real-time operation of the model, i.e. the calculation time is the same or even shorter than the time of casting.

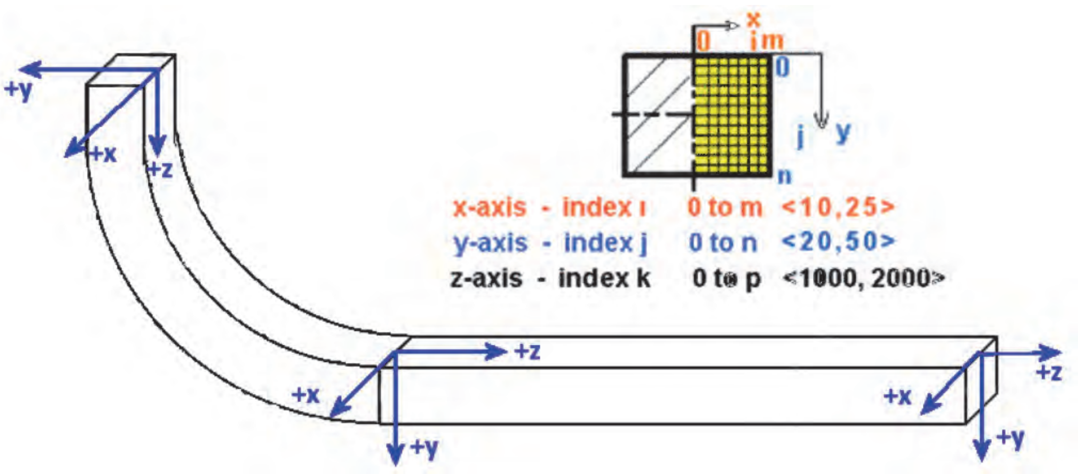

Fig. 3 Scheme of the network and the definition of the coordinate system
Obr. 3 Schéma výpočtové sítě a definice souřadného systému

The initial condition for the solution is the temperature at individual points of the calculation mesh. A suitable value is the highest possible temperature, i.e. the casting temperature. An explicit finite difference method is used to solve the model. It follows from its principle that the stability of the calculation depends on the size of the time step. In the model, the method of adaptive change of the calculation step is implemented, i.e. the user-specified calculation step is considered as recommended and the software changes it during the calculation.

The diagram in Fig. 4 shows the distribution of the boundary conditions to the zone of the mould (primary cooling zone), the secondary and the tertiary cooling zone. It is not possible to set different cooling around

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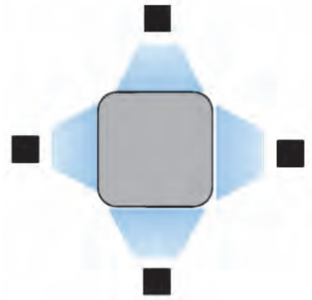
the section in the tubular mould or under the water nozzles, i.e. not on a small or a large radius or on both sides. A number of the support rollers are much smaller than on the slab CCM and virtually no heat flow escapes through them. Even for boundary conditions, their dependence on the continuously cast blank surface temperature is respected. Therefore, the non-linearity of the task is even more intensified. The process of billet cooling in all three cooling zones differs from the cooling of slabs on the slab CCM [2, 3, 13].

a) Mould
a) Krystalizátor



b) Nozzles in the secondary cooling
b) Trysky sekundárního chlazení

c) Support rollers
c) Vodící válce

d) Natural convection and radiation
d) Přirozená konvekce a radiace

Fig. 4 Diagram of the boundary conditions in different places of a billet caster
Obr. 4 Schéma okrajových podmínek v různých místech sochorového ZPO

Due to the fact that the task can be according to Figs. 3 and 4 considered axially symmetrical, it is sufficient to solve only half of the cross-section, that is why the definition of the boundary conditions is described by equations (11a) to (11e). T_{cast} is the casting temperature, T_{surface} and T_{amb} are the surface temperature of the billet and the ambient temperature, n is normal line to the billet surface, σ is the Stefan-Boltzmann constant, ε is the emissivity (relative radiance), k is the thermal conductivity, q is the heat flow and htc is the heat transfer coefficient (convection).

1. $T = T_{\text{cast}}$ molten steel level (11a)
2. $-k\frac{\partial T}{\partial n} = 0$ plane of symmetry (11b)
3. $-k\frac{\partial T}{\partial n} = htc \cdot (T_{\text{surface}} - T_{\text{amb}})$ in the mould (11c)
4. $-k\frac{\partial T}{\partial n} = htc \cdot (T_{\text{surface}} - T_{\text{amb}}) + \sigma \cdot \varepsilon \cdot (T_{\text{surface}}^4 - T_{\text{amb}}^4)$ in the secondary and tertiary zone (11d)
5. $-k\frac{\partial T}{\partial n} = q$ under guide rolls (11e)

2.1 Tubular mould

The walls of the tubular mould (Fig. 5) are cooled by one cooling circuit, in which the temperature difference of the inlet and outlet water and the flow of water are measured. Control system for mould cooling maintains a constant water flow rate specified by the operator.

The issue of boundary conditions in the mould is so complex that it requires an implementation of a proprietary model that must be tuned on the basis of operating data from experimental temperature measurements in the mould walls by thermocouples and from the measurement of temperatures under the mould by pyrometers. It is possible to determine an average heat flow dissipated from the mould [6]. Its value must be consequently separated to individual walls along their height and width.

Method of calculating heat flows on the mould wall

The diagram of the tubular mould and location of the thermocouples in its wall is shown in Fig. 5. Fig. 6 shows an example of the measured temperatures. These diagrams represent the time interval of one heat for steel grade TERMEX-1. It is evident from the diagrams that the measured values cannot be directly used in the calculation of heat flows, but they must be filtered (evolutions of the measured temperatures are in the diagram plotted with a thick line).

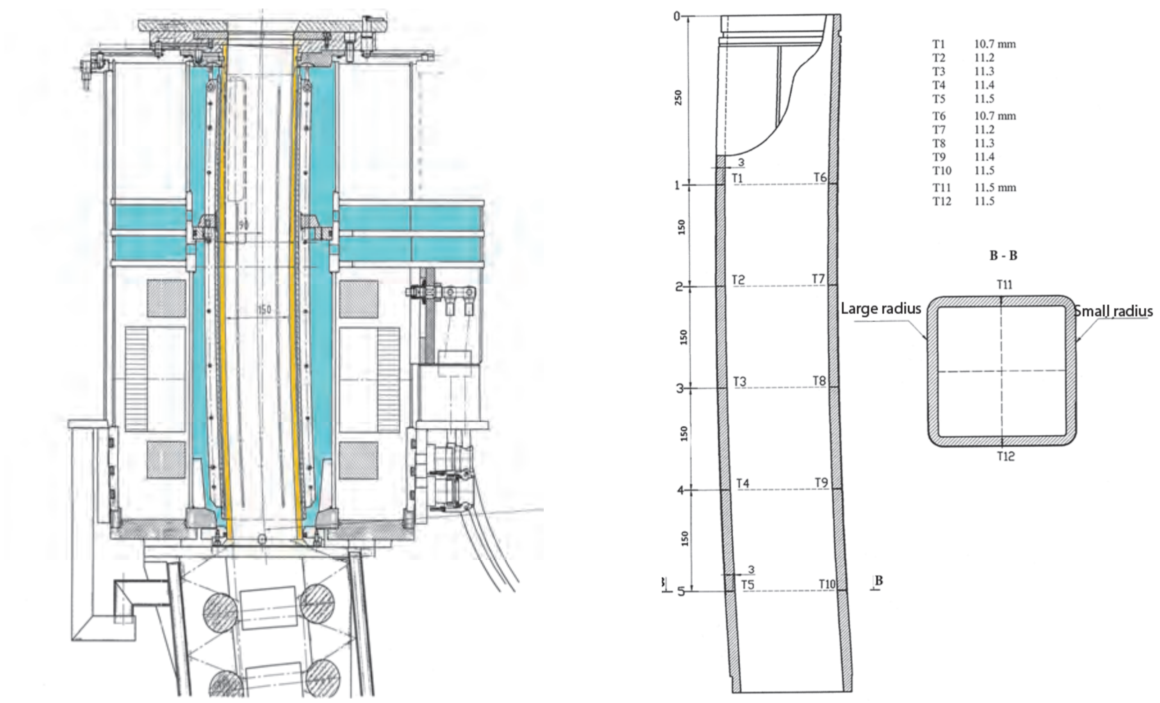


Fig. 5 Diagram of the tubular mould and position of thermocouples
Obr. 5 Schéma trubkového krystalizátoru a umístění termočlánků

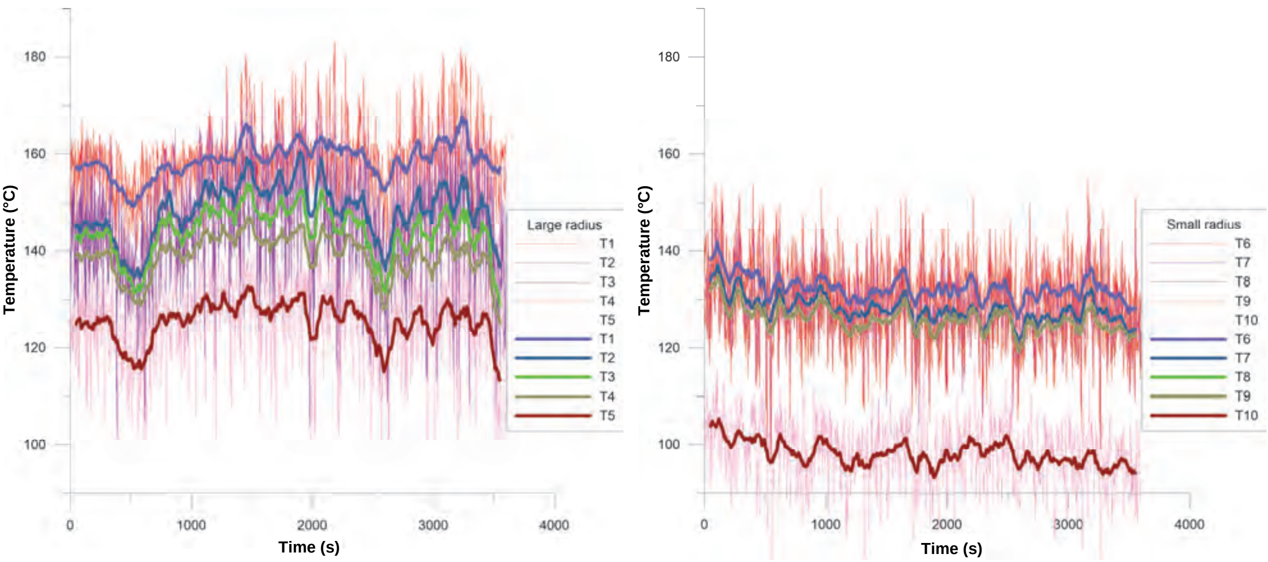


Fig. 6 Examples of measured temperatures in the mould wall
Obr. 6 Příklady změřených teplot ve stěně krystalizátoru

Fig. 7 shows a simplified diagram of the mould heat balance and a diagram of wall temperature measurement using thermocouples [6]. The distance of the measuring point of the thermocouple δ_B from the mould inner wall is 3 mm. The heat balance is solved for five sections of the mould chosen in a way that the thermocouples are positioned vertically and approximately in their centre. The basic prerequisite for this solution is that equality of the heat outputs from the cooling water flow and heat passage is ensured not only for the whole mould, but also for all five calculation sections. The same value of the heat transfer coefficient on the side of the cooling water in all sections is assumed for the calculation. It requires solution of a system of equations.

The value of the heat transfer coefficient htc_w on the mould outside wall (on the side of the cooling water), chosen for the heat balance calculations, must correspond, with a certain tolerance, to the calculation value of this quantity from the usual criteria dependences for water flow through the channel of the annular cross section (mould shell). For example, this coefficient for the flow rate of 1665 $l \cdot min^{-1}$ is approximately 30,000 $W \cdot m^{-2} \cdot K^{-1}$.

The heat transfer is solved for the surfaces of the mould inner wall, the surface which depends on the height of the respective section 1 to 5, separately on the big and small radii of the billets bending and on both its side

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walls. At the section 1, the height depends on the distance of the liquid metal level from the mould upper edge h_{level}. The diagram in Fig. 7 shows evolutions of the specific heat flows along the mould height on the big and small radii of the mould during casting of the steel grade TERMEX-1. It is an example of the approach presented here of determining the boundary conditions in the mould from the measured temperatures in the walls of the tubular insert and from the temperature difference of the cooling water and its flow. In this way, over 280 different heats were processed. The obtained results were correlated with the following influences: carbon content in the cast steel, contraction of cast steels, casting speed, electromagnetic stirring in the mould, type of casting powder, negative strip size, molten steel level in the mould, etc.

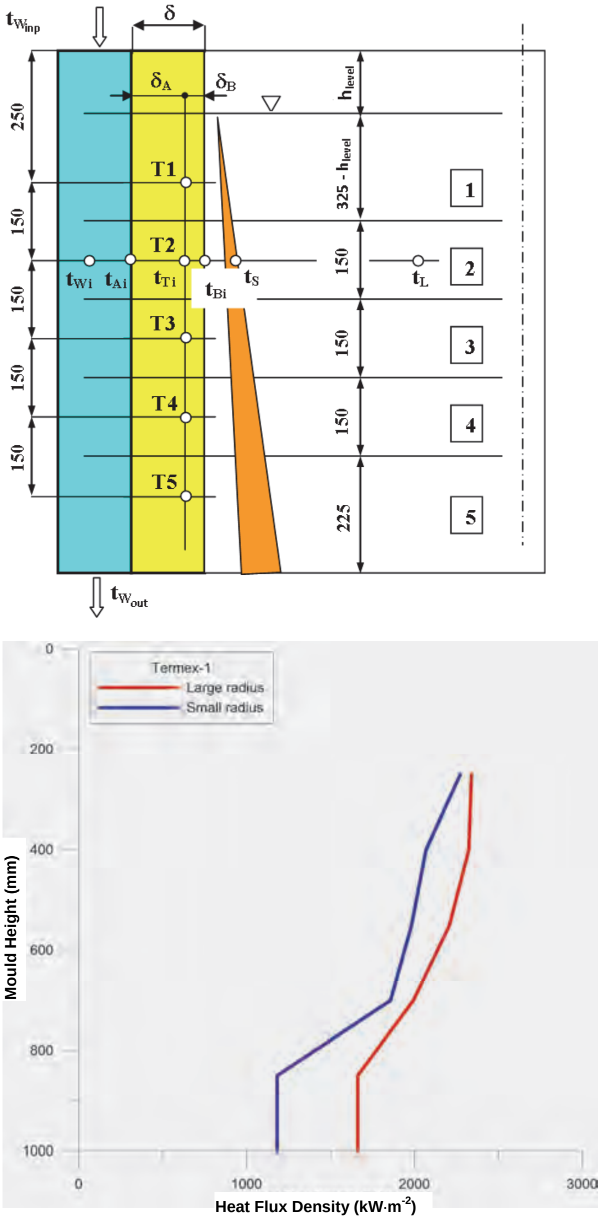


Fig. 7 Diagram of the heat balance of a mould and of calculated heat flows

Obr. 7 Schéma tepelné bilance krystalizátoru a vypočtených tepelných toků

2.2 Determination of heat transfer coefficients in the secondary and tertiary zones

The boundary conditions in the secondary cooling area are illustrated in Fig. 8. It is apparent that the boundary conditions must be defined for three different characteristic surfaces of the continuously cast blank according to their position relative to the roll and reach of the spray nozzle. Cooling by water nozzles has critical influence. Therefore, a great deal of attention must be given to the determination of the appropriate heat transfer coefficient under the nozzle (forced convection).

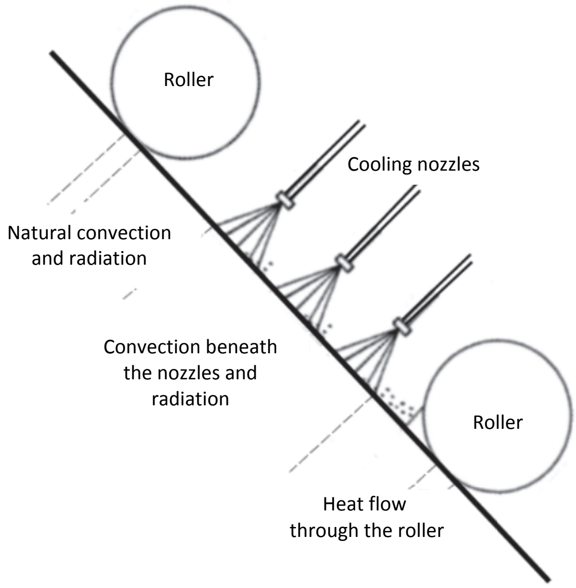


Fig. 8 Diagram of cooling in the secondary zone

Obr. 8 Schéma chlazení v sekundární zóně

2.2.1 Heat transfer coefficients under the cooling nozzles

Commercially used temperature field models describe the heat transfer coefficients under the nozzles as a function of the incident amount of water per unit of area. They are based on a variety of empirical relationships. We cannot recommend this approach. In the presented model, the heat transfer coefficients are obtained by measuring the spray characteristics of all the nozzles used on the CCM in the so-called hot-plate model (Fig. 9) in the Heat Transfer and Fluid Flow Laboratory at Brno University of Technology, Faculty of Mechanical Engineering [9, 10], for a sufficient range of operating pressures of water and sufficient range of the casting speed.

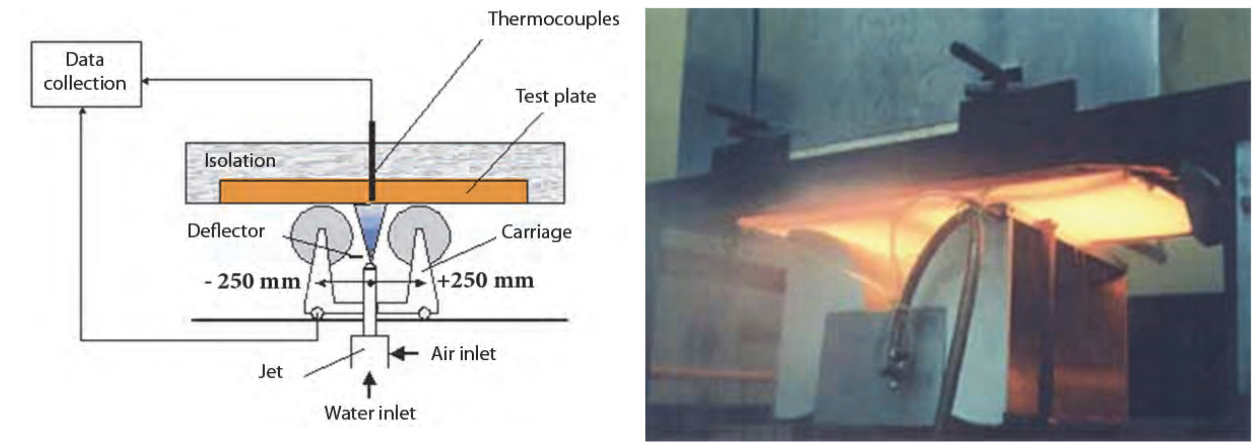
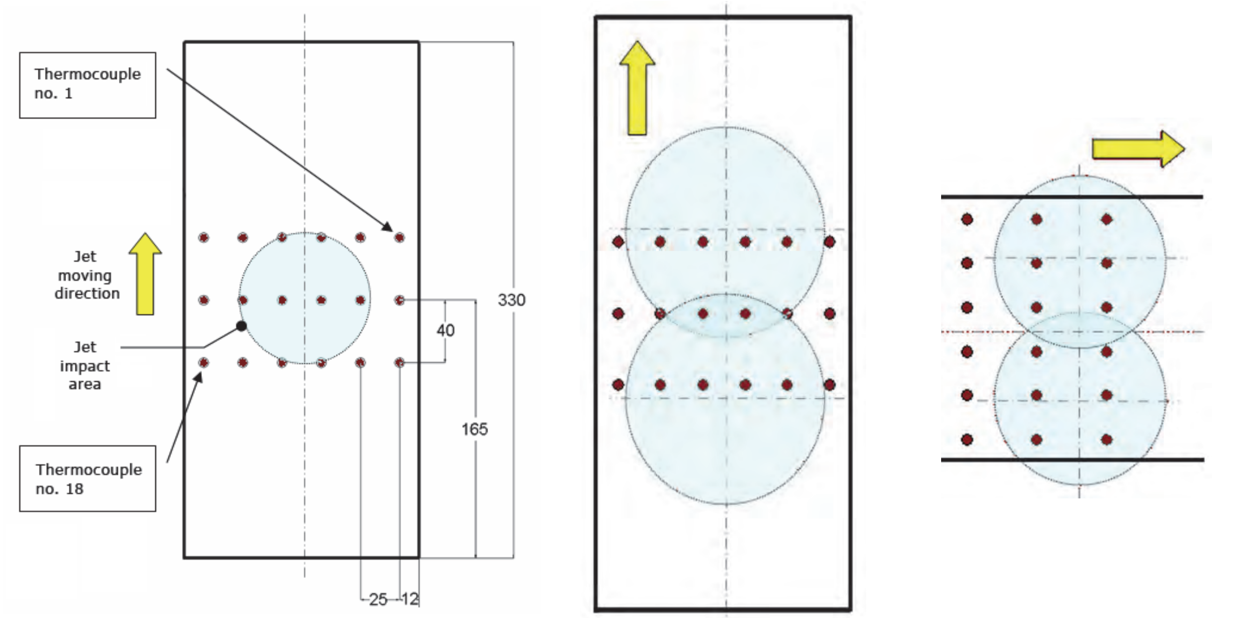


Fig. 9 Laboratory device simulating the process of cooling
Obr. 9 Laboratorní zařízení k simulaci chladicího procesu



The plate for the measurement of one nozzle
Deska při měření jedné trysky

The plate for the measurement of two serial nozzles
Deska při měření dvou trysek za sebou

The plate for the measurement of two parallel nozzles
Deska při měření dvou trysek v řadě

Fig. 10 Diagram of the layout of thermocouples on the model plate
Obr. 10 Schéma rozmístění termočlánků na modelové desce

The steel plate with thermocouples is mounted in the holder. The plate is electrically heated. During the experiment, a nozzle with a motion mechanism is inserted under the plate (the heater is at this time removed). During the experiment, water is pumped into the nozzle from the reservoir by a pump. The water pressure is measured before entering the nozzle. The temperature of the water and the temperature inside the plate are monitored by a computer measurement system. Examples of the layout of the measuring points on the plate are shown in Fig. 10. Square dimensions of the measuring plate are 330 × 150 mm, the thickness is 24 mm. Eighteen thermocouples (diameter 1.5 mm, type K) are built into the plate. The set of thermocouples measures the temperature at a depth of 2.5 mm (measured from the cooled surface). The top surface of the plate is insulated. The bottom of the plate is cooled. The nozzle (or nozzles) are placed on a movable support. Due to the fact that the casting machine is operated at a large range of casting speeds, the experiments were performed for casting speeds of 1.5 and 4.0 m·min^{-1}. In this way, more experiments were performed for each nozzle for different water flows.

From the heat transfer coefficients, a database of boundary conditions is constructed, from which the interpolation model determines the respective heat transfer coefficient under the nozzle for the desired temperature of the surface of the continuously cast blank, the operating pressure of the water and the desired casting speed. The temperature of the water in the secondary zone is entered into the model as an ambient temperature T_{amb} under the nozzles, the ambient is entered into the model as an ambient temperature

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[11]. This approach represents a unique combination of experimental measurements in laboratories with a numerical model for calculating non-linear boundary conditions under a cooling nozzle.

Due to the fact that control of secondary cooling is performed by regulation of water flow and not by regulation of its pressure, the functions water, flow-water pressure were set for all the nozzles according to the manufacturer's laboratory model, in order to set for the experiments the pressure corresponding to the flow in the zone:

$$\dot{m} = \sqrt{p} \cdot k \qquad p = \frac{\dot{m}^2}{k^2} \tag{12}$$

where p is water pressure (MPa), $\dot{m}$ is water flow (l·min^{-1}) and k is nozzle constant.

For each point of the calculation mesh, we know its temperature and position relative to the nozzles. For each point on the surface, it is possible to assign a four-dimensional state space, in which the following coordinate system is introduced: (htc, p, w, T) where htc is the heat transfer coefficient (W·m^{-2}·K^{-1}), p is the water pressure (MPa), w is the casting speed (m·min^{-1}) and T is the temperature. In this area, the heat transfer coefficient is a function of the flow, speed, and temperature, i.e. $htc = f(p, w, T)$. The f function is not known, only some htc coefficients are known for some flows, temperatures, and speeds. Therefore, the function f is replaced with a new function derived from the known measured values. For the calculation of relations (12) we have coefficients for the dependence of the flow and speed.

The cooling effect of the nozzle can be assessed differently, e.g. according to the maximum value of the heat transfer coefficient under the nozzle, according to the average value of the coefficient, etc. However, it seems to be most appropriate to assess it according to the value of the heat flow determined from the equation (13), which the nozzle dissipates from the cooled surface:

$$\dot{Q} = 2 \cdot \int_0^{x_{max}} \int_{-z_{min}}^{+z_{max}} htc_{xz} \cdot \left(T_{\text{surface}} - T_{\text{amb}}\right) \cdot \mathrm{d}x \cdot \mathrm{d}z \quad \text{(W)} \tag{13}$$

where:

htc_{xz} – heat transfer coefficient under the nozzle at the coordinates x and z,

T_{surface} – steel surface temperature; it is here considered to be constant over the whole area,

T_{amb} – ambient temperature; cooling water temperature of 20 °C is considered here.

$x_{\max}$ – billet cross section size 150 mm,

$z_{\min}$, $z_{\max}$, – the interval for which the nozzle experiment was performed; typical value $z_{\min}$ = 260 mm, $z_{\max}$ = 200 mm.

In relation to the dependence of heat transfer coefficients on the continuously cast blank surface temperature, it is necessary to mention the so-called Leidenfrost temperature [10]. It is the surface temperature, at which the character of heat transfer significantly changes. The continuous steam layer formed on the surface at high temperatures is disrupted and the heat transfer coefficients increase by a jump. Significantly more intense drops of surface temperature during passage under the cooling nozzle also correspond to this state.

The resulting heat flows calculated according to the equation (15) for surface temperatures of 500, 700, 900 and 1100 °C, in dependence on the water flow, are plotted in Fig. 11. Fig. 12 shows the measured values of the heat transfer coefficients processed by software of the temperature model in the form of 3D and 2D diagrams under the nozzle. These diagrams are plotted for the surface temperature of 800 °C, for the speed of 2.8 m·min^{-1}, for the water flow of 10 l·min^{-1} and for two nozzles JATO 4065L.

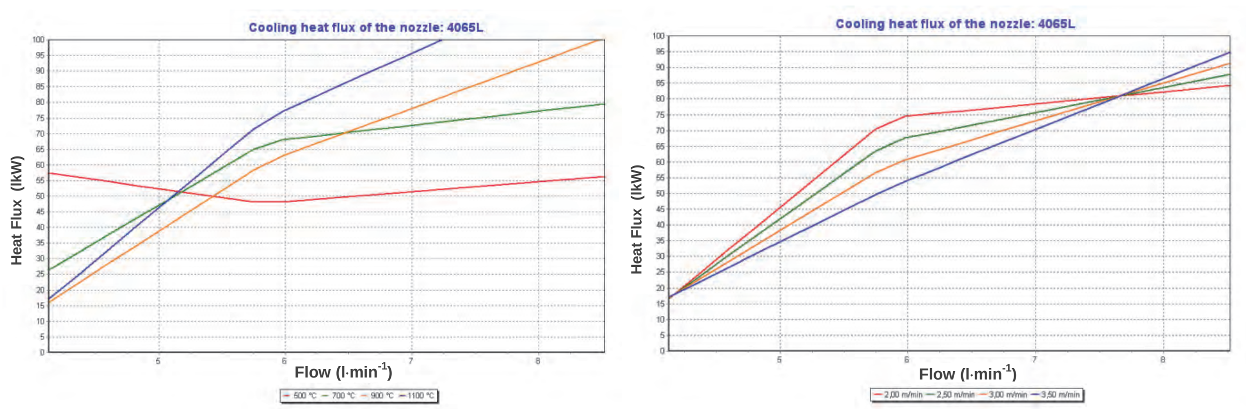

Fig. 11 Heat flow with the use of the nozzle 4065L (two serial nozzles) in dependence on the water flow rate and on the surface temperature
Obr. 11 Odvedený tepelný tok pomocí trysky 4065L (2 trysky v řadě) v závislosti na průtoku vody a povrchové teplotě

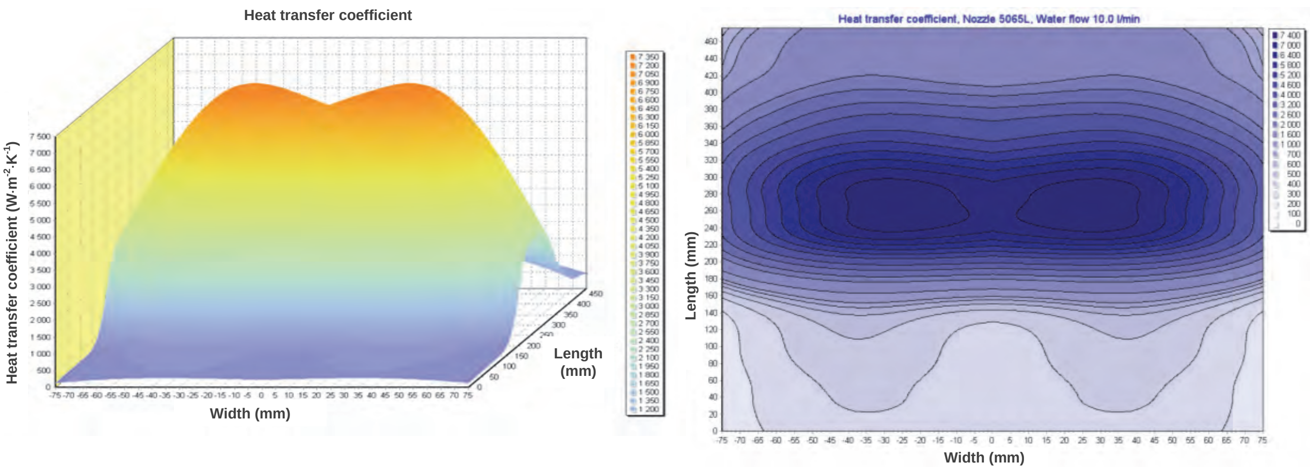

Fig. 12 Heat transfer coefficient for two serial nozzles with the water flow rate of 10 l·min^{-1} through each nozzle
Obr. 12 Součinitel přestupu tepla pro 2 trysky v řadě při průtoku 10 l·min^{-1} každou tryskou

2.2.2 Heat transfer coefficients in the area of the rollers

The billet CCM has a small number of support rollers. Rollers in the pulling and straightening stand have more significant influence on the heat flows. The heat dissipated by the rollers in the billet CCM is, therefore, negligible (it cannot be neglected in the case of the slab CCM, though). The greater importance of the influence of rollers is caused by the fact that they separate the areas, into which the nozzles can spray. The boundary condition below the roller is therefore used also for limiting the influence of nozzle action [8].

2.2.3 Heat transfer coefficients in the tertiary cooling zone

A heat transfer through natural convection is considered from those parts of the continuously cast blank surface that are not cooled by the nozzles or that are not in contact with the roller. The empirical relation [12, 13] is used for the heat transfer coefficient htc_{nat}:

$$htc_{nat} = 0{,}84 \cdot \sqrt{(T_{surface} - T_{amb})} \qquad (\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}) \qquad (14)$$

2.2.4 Heat transfer by radiation

The entire billet surface, with the exception of areas in contact with the rollers, is subject to radiation. Consequently, the reduced heat transfer coefficient from the radiation must be added to all the heat transfer coefficients discussed in the previous paragraphs, in which the relative radiation ε is considered to be a variable, σ is the Stefan-Boltzmann constant, $T_{surface}$ is the surface temperature and T_{amb} is the ambient temperature

$$htc_r = \varepsilon \cdot \sigma \cdot (T^2_{surface} + T^2_{amb}) \cdot (T_{surface} - T_{amb}), \; (\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}) \quad (15)$$

Fig. 13 shows the evolution of the calculated reduced heat transfer coefficient from radiation in relation to the variable emissivity (blue curve) according to the equation (15) and for constant relative radiation ε = 0.8 (red curve).

$$\varepsilon = 0{,}788285 + 7{,}0003375 \cdot T_{surface} - 40{,}1785714 \cdot 10^{-8} \cdot T^2_{surface} \;, \qquad (16)$$

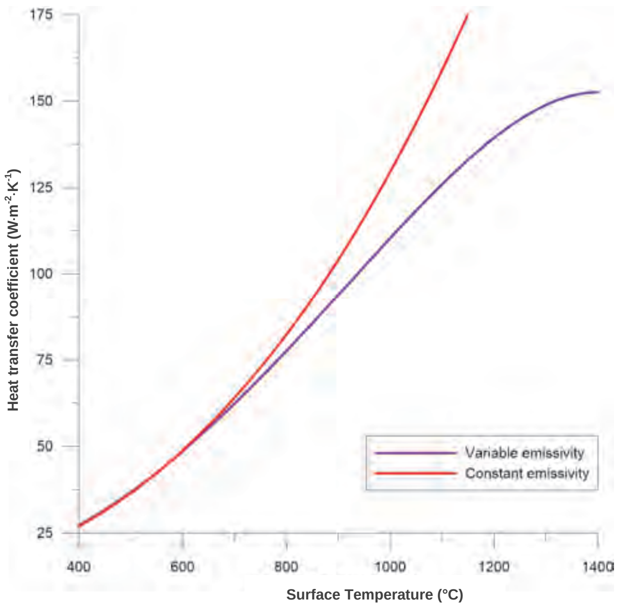

Fig. 13 Evolution of the reduced heat transfer coefficient from the radiation
Obr. 13 Průběh redukovaného součinitele přestupu tepla od radiace

2.2.5 Total heat transfer coefficient

The total heat transfer coefficient is determined as a sum of two partial heat transfer coefficients - the heat transfer coefficient of actual heat transfer (natural or forced convection) and the reduced heat transfer coefficient from the radiation. Radiation was thus recalculated to convective heat transfer (to natural convection). The natural convection coefficient is

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determined according to equation (14), the forced convection coefficient under the cooling nozzles is determined by the described laboratory measurements and the reduced coefficient is determined by the equation (15) or (16).

The flow rate of the total heat transfer coefficient, for example, on the billet side wall along the entire CCM, is shown in Fig. 14 for individual cooling zones from the mould (Kr) to the zone IV (Fig. 1). It is also possible to evaluate the evolution of the total coefficient on the big and small radius of the billet bending [8]. The coefficient is formed by a single component only at the contact of the billet and the roller. The secondary cooling nozzles are on the CCM divided into several separate control loops, which makes it possible to form temperature field of the continuously cast blank.

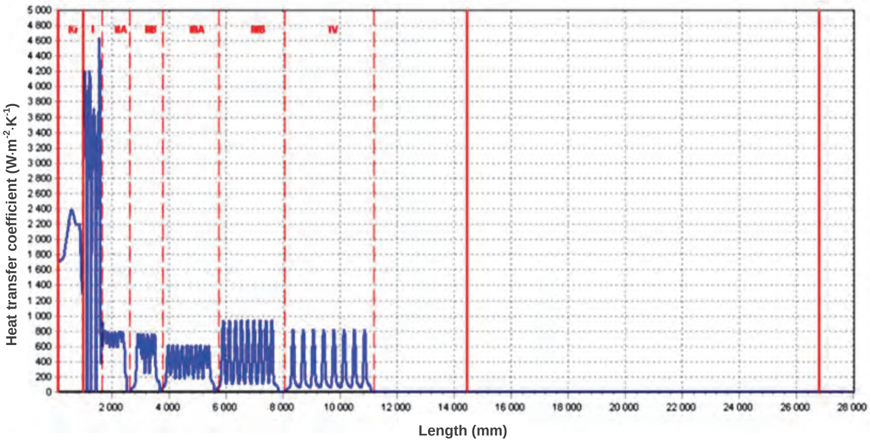

Fig. 14 Total heat transfer coefficient on the side wall along the entire caster
Obr. 14 Celkový součinitel přestupu tepla na boční stěně sochoru podél celého stroje

3. Thermo-physical properties of steel

Thermo-physical properties of steels belong among important parameters entering numerical models that solve the temperature field of the continuously cast blank. At application of the mentioned simulation of development of latent heats of phase and structural changes by introduction of enthalpy, it follows from the Fourier-Kirchhoff equation (1) that formation of the temperature field of the billet passing through the CCM is directly affected by the following thermo-physical properties: volume enthalpy, specific heat capacity, thermal conductivity coefficient and density (specific density) of steel.

The Finnish solidification model Interdendritic Solidification Model (IDS) is used to determine the temperature dependence of these parameters of steel in the presented simulation of solidification. It is a simulation tool for solidification of steel comprising phase changes, which makes it possible to determine the dependence of the basic thermo-physical properties on the temperature for the given steel grade with a specific chemical composition and for the desired parameters of cooling. The model of solidification IDS is a so-called gray box, i.e. it combines empirical or semi-empirical sub-models with physically conceived (fundamental) sub-models [14].

CCM in real operation cast even hundreds of different steel grades, for which it would be difficult to set the parameters of casting and other related technological parameters. The chemical composition of steel, according to which the steel is classified into quality groups (that are further divided into sub-groups), influences significantly the susceptibility of the given steel grade to the occurrence of defects, namely crack formation and phenomena of segregation in the continuously cast blank. Although the role of individual chemical elements and of their combinations is not always quite unambiguous, it is generally possible to mention the basic trends of some influences of elements, especially carbon, on the susceptibility of cast steels to defects. Depending on the carbon content, the steel is usually divided into four groups. The first group consists of steels with a content of C < 0.08%, the second group contains steels with a C content from 0.08 to 0.15%, the third group contains steels with a C content from 0.15 to 0.50%, and the fourth group contains steels with a C content > 0.50% [2].

The basic recommended steel composition of steels for the casting of billets is given in Tab. 1. The table lists one to two characteristic steels for each of the four groups. It is supplemented with liquidus and solidus temperature. The mentioned IDS software was used for determination of thermo-physical parameters on the basis of the chemical composition of the steels [15].

The results of the solution of the temperature field of the billet with dimensions 150 × 150 mm are shown for the steel grade TERMEX-1 from Group 3. Therefore, Figs. 15 and 16 show diagrams of the dependence of the thermo-physical properties on the temperature (thermal conductivity, specific heat capacity, density, enthalpy), which are supplemented with the liquidus and solidus temperature.

Tab 1 Distribution of steel grades into groups and sub-groups according to their chemical composition
Tab. 1 Rozdělení ocelí do skupin a podskupin podle chemického složení

Sk	Family	Steel	T_{LIK}	T_{SOL}	C	Mn	Si	P	S	Cu	Cr	Ni	V	Ti
			(°C)		(weight %)									
1	C15	P2-04B	1531	1489	0.020	0.300	0.040	0.010	0.010	0.065	0.050	0.040	0.000	0.000
2	B20	1220	1523	1477	0.100	1.025	0.075	0.010	0.010	0.060	0.075	0.075	0.015	0.000
3	A31	TERMEX-1	1515	1457	0.180	0.725	0.200	0.020	0.020	0.200	0.075	0.075	0.000	0.000
	D50	C45EKL	1491	1402	0.460	0.650	0.300	0.015	0.015	0.100	0.200	0.200	0.000	0.000
4	B73	C82DPC	1466	1342	0.840	0.700	0.200	0.008	0.007	0.125	0.085	0.100	0.000	0.000

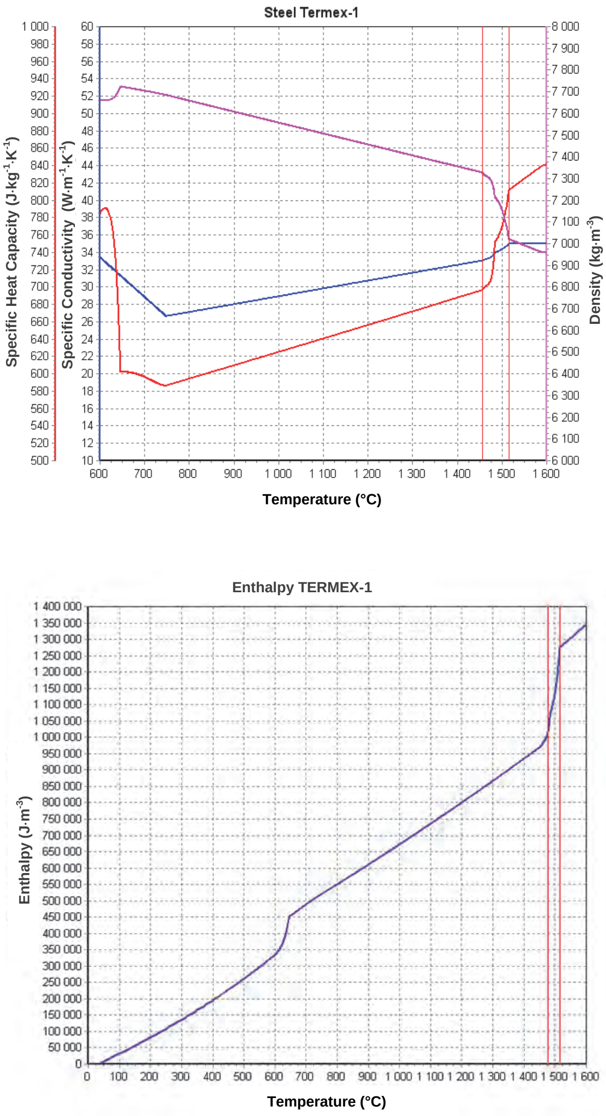

Fig. 15 Thermo-physical properties of the TERMEX-1 steel grade from the group No. 3
Obr. 15 Termofyzikální vlastnosti oceli TERMEX-1 ze skupiny 3

4. Methods of displaying the calculated temperature field of the billet

Fig. 16 contains one of the most illustrative views provided by the presented model. Each curve here records the temperature history of any cross-sectional point selected by the user when it passes through the entire CCM from the molten steel level in the mould (coordinate 0) to the flame cutting machine. Typical points (points in the corners and in the centre of the square profile) are selected here.

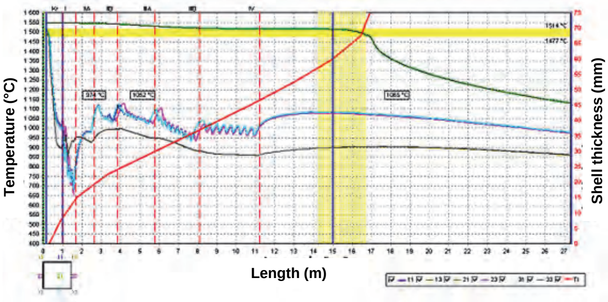

Fig. 16 Temperature history of selected points of the cross section of the billet 150 × 150 mm (steel TERMEX-1) during its passage through the caster
Obr. 16 Teplotní historie zvolených bodů příčného řezu sochorem 150 ×150 mm (ocel TERMEX-1) při jeho průchodu ZPO

The red curve, which runs from the start of the coordinate system and has a scale in the diagram at the right-hand side, shows the increase of the solidified strand shell. The width of the horizontal yellow strip shows the temperature range of solidification for the steel grade TERMEX-1 (here 1457 - 1515 °C). The width of the vertical yellow zone indicates the distance between the iso-liquidus and the iso-solidus (the width of the mushy zone) at its maximum value, as shown also in Fig. 17. The red dashed vertical lines are the boundaries between the individual cooling zones already mentioned above, the blue vertical lines represent the level of the molten steel in the mould, the mould lower edge, the end of the arc and the position of the flame cutting machine. In addition, the surface experimental temperatures measured by pyrometers on real CCM (974 °C, 1052 °C and 1065 °C) at the given locations are expressed numerically below the diagram in the frame.

Fig. 17 shows evolution of the iso-liquidus (red curve) and of iso-solidus (blue curve) in the longitudinal axial section of the billet. Fig. 18 shows isothermal surfaces in transverse and longitudinal sections of the billet displayed on the computer monitor connected to the CCM information system.

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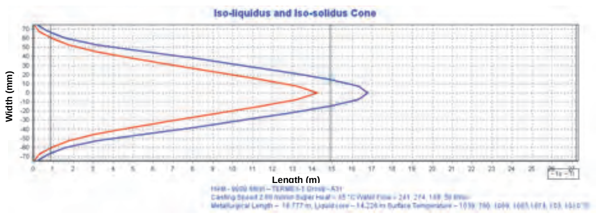

Fig. 17 Evolution of iso-liquidus and iso-solidus in the axial longitudinal section of the billet 150 × 150 mm (steel TERMEX-1)

Obr. 17 Průběh izolikvidy a izosolidy v podélném osovém řezu sochorem 150 × 150 mm (ocel TERMEX-1)

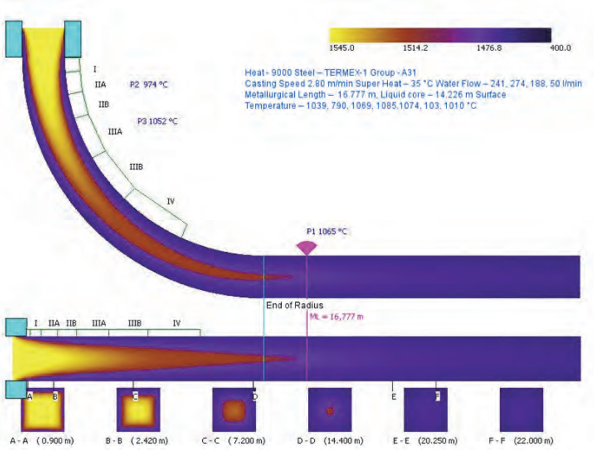

Fig. 18 Iso-thermal areas of of the billet 150 × 150 mm (steel TERMEX-1) displayed on the monitor

Obr. 18 Izotermické plochy sochoru 150 × 150 mm (ocel TERMEX-1) na monitoru

Conclusions

The paper presents a proposal of a complex calculation apparatus for solving the temperature field of the continuously cast billets from the automatic generation of the mesh through the preparation of the thermo-physical parameters (including the assessment of their influence on the accuracy of the calculation), through to the definition of the boundary conditions (including the assessment of their impact on the calculation accuracy) and various processing of its results. This proposal was implemented in cooperation with the steelworks Třinecké železárny, a.s. as the main solver of the project of the Ministry of Industry and Trade of Czech Republic. An overview of the numerical model and preparation of its use is presented. The most difficult is the definition of the boundary conditions on all the surfaces of the system that separate the solved system of the billet from the so-called surroundings, or which lie in the planes of the billet symmetry. For determination of the heat transfer coefficients under the cooling nozzles it is necessary to perform an experiment with a hot plate method. Verification and application of the numerical model of temperature field assume also systematic experimental research and measurement of operational parameters on real CCM.

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Proces na nejvyšší úrovni – Salzgitter Flachstahl vyvinul nový způsob high-tech odlévání

aktiv-online.de *07.03.2017*

Lehká, extrémně pevná, dobře tvářitelná – to jsou vlastnosti nové vysoce výkonné oceli, zajímavé pro automobilní a strojírenský průmysl. Mimořádné na ní je, že Salzgitter Flachstahl tuto ocel vyrábí inovativním způsobem. Ocel o teplotě 1500 °C teče z pánve na dopravní pás 12 m dlouhého zařízení pásového lití, světové novinky a jádro nového inovativního lití oceli. Technologii vyvinuly Salzgitter Flachstahl, SMS a univerzita v Clausthal-Zellerfeld. Mimořádné na způsobu je, že se všechno pohybuje horizontálně. Zatímco u obvyklého plynulého lití proudí ocel formou shora dolů a vytváří až 50 cm silné předlitky, je nyní vedena vodorovně na vodou chlazeném dopravním pásu. To má jasné výhody: vznikající pásy jsou jen 1,5 cm silné. Tavenina se ochlazuje mnohem rychleji, a tím se vytváří jemnější struktura s vysokou kvalitou. „Tímto způsobem se mohou vyrábět vysoce výkonné oceli, které se konvenčními způsoby vůbec nedají vyrobit," vysvětluje Dirk Austemann z firmy SMS, stavitele zařízení. Používaná ocel má vysoký obsah manganu, jakož i křemíku a hliníku.

Povzbuzovací prostředky pro unavenou ocel

Wissenschaft-aktuell.de *13.03.2017*

Po mnoha letech se mohou ocelové slitiny v mostech, letadlech nebo elektrárnách unavit. Mikrotrhliny se šíří a náhlá zatížení vedou k lomům s částečně katastrofálními následky. Velká stabilita vzrostlých kostí zavedla nyní mezinárodní skupinu materiálových vědců k efektivní strategii proti unavujícím se ocelím. Jak informují tito vědci v časopise „Science“, mohla by uměle zkonstruovaná, hierarchicky vybudovaná nanostruktura propůjčit materiálům výrazně delší život. Přeneseno na velké množství ocelových slitin by se tak měla výrazně zvýšit stabilita stavebních děl, železnic a jiných ocelových konstrukcí. „Zatížení strukturálních komponent jsou často cyklická,“ říká Cemal Cem Tasan z massachusetského institutu technologií v Cambridgi. Jednotlivá zatížení, zaviněná střídáním teplot a vibracemi, jsou sice podkritická, ale pokud se mnohotisíckrát opakují, vedou k únavě materiálu a nakonec k lomu materiálu. Vědci se přitom nechali inspirovat komplexní mikro- až nanostrukturou vnitřní konfigurace kostí.

Více peněz pro oceláře – čtyři procenta ve dvou stupních

zeit.de *17.03.2017*

Zhruba 72 000 zaměstnanců severoněmeckého ocelářského průmyslu by mělo ve dvou stupních dostat celkem 4 % více na mzdách. Dohodli se na tom zaměstnavatelé a odboráři z IG Metall po více než desetihodinovém jednání v Düsseldorfu. Ve dnech před rozhodujícím jednáním vyzvaly odbory k celé sérii varovných stávek, kterých se podle odborů zúčastnilo 13 500 ocelářů. Zaměstnavatelé nejprve nabízeli jen 1,3 % pro 15 měsíců, zatímco odbory požadovaly o 4,5 % více peněz na období 12 měsíců. Kompromis nakonec vypadá tak, že od 1. dubna 2017 dojde ke zvýšení o 2,3 % na 13 měsíců a od 1. května 2018 o dalších 1,7 %. Dohoda platí do 31.12.2018, a sice pro Severní Porýní-Vestfálsko, Niedersachsen a Brémy. Pro zaměstnance v Sársku a východním Německu jsou vedeny samostatné rozhovory. Nils Naujok ze strategického poradenského domu PwC konstatuje, že zakázkové knihy většiny podniků jsou plné. Vzhledem ke zvýšení cen mezi 10 a 15 % v uplynulém roce se mohou podniky těšit ze stoupajících marží. Přesto zůstává odvětví i v letošním roce pod tlakem.