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USE OF NUMERICAL SIMULATIONS DURING CONTINUOUS STEEL CASTING

VYUŽITÍ NUMERICKÝCH SIMULACÍ PŘI KONTINUÁLNÍM ODLÉVÁNÍ OCELI

Abstract

This paper describes numerical modeling of round billets solidification process during continuous steel casting. Emphasis is placed not only on the mathematical nature of transmission events that affect the casting billet (heat conduction, convection and radiation), but also the methods of solving thermal problems (analytical, numerical). The numerical methods are discussed in detail the finite element method and the method of networks that form the core of the most common commercially used simulation software for modeling the temperature fields at various technological processes.

In the research was compiled its own sophisticated software - **Tefis** - solving the problems of temperature fields by using of an explicit (numerical) method of networks. The actual solution is implemented using Fourier-Kirchhoff equation in differential form of enthalpy, which includes the velocity of solidified billet.

By software **Tefis** are carried out a series of computer simulations and sensitivity analysis method to examine the effects of different levels of steel in a mould, different casting velocities, different temperatures above the liquidus temperature of steel and different intensity in the secondary cooling zone on the overall temperature field of continuously casted billets. Thus the calculated temperature fields, of declared steel marks, are subsequently confronted with the results of experimental measurements on real operating casting machine.

Abstrakt

Předkládaný příspěvek se zabývá popisem a numerickým modelováním procesu tuhnutí kruhového předlitku, při plynulém odlévání oceli. Důraz je kladen nejen na matematickou podstatu přenosových jevů, které působí na odlévaný předlitek (sdílení tepla kondukcí, konvekcí a radiací), ale také samotným metodám řešení tepelných úloh (analytické, numerické). Z numerických metod jsou zde podrobněji rozebrány metody konečných prvků a metody sítí, které tvoří nejčastější jádra komerčně využívaných simulačních softwarů pro modelování teplotních polí při nejrůznějších technologických procesech.

V rámci výzkumu byl sestaven vlastní sofistikovaný software – **Tefis** – řešící problematiku teplotních polí prostřednictvím explicitní (numerické) metody sítí. Vlastní řešení je realizováno pomocí Fourierovy-Kirchhoffovy rovnice v diferenční entalpické formě, která zahrnuje rychlost tuhnoucího předlitku.

Softwarem **Tefis** jsou provedeny série počítačových simulací a metodou citlivostní analýzy se zkoumaly vlivy rozdílné hladiny oceli v krystalizátoru, rozdílné licí rychlosti, rozdílné teploty oceli nad teplotou likvidu a rozdílné intenzity chlazení v sekundární zóně na celkové teplotní pole plynule

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litého předlitku. Takto vypočtená teplotní pole, deklarovaných skupin ocelí, jsou následně konfrontována s výsledky experimentálního měření na reálném provozním licím stroji.

1 METHODS OF TEMPERATURE EXERCISES SOLUTION

Temperature field of casted billet it's possible to solve by analytical methods or numerical, or by the methods of mathematical or physical modeling. Each of these methods has certain advantages and disadvantages of their mathematical nature.

Analytical methods

These methods provide solutions to the exercise in the form of a mathematical expression for the temperature as a function of spatial coordinates and time. The solution must conform to certain conditions and the uniqueness of the equation. These methods include Method of separation of variables (Fourier method), the method of Green functions, Fourier and Laplace transform, Bessel (Hankel, Neumann) function, the method of superposition, etc. To solve thermal problems, these methods generally limited use, because even simple problems in the area heating or cooling wire largely led to complex results in the form of a sum of infinite series, exponential functions, etc - see equation (1). Overall, the authors use to solve a variety of simplifying assumptions, for its own calculation, and the implementation of boundary conditions which determine the need for custom solutions.

$$\left(\Theta_{\mathrm{k}}-1\right)\cdot\frac{e^{-\mathrm{Fo}^2}}{\mathrm{erf}(\mathrm{Fo})}-\frac{\sqrt{K_{\mathrm{a}}}}{K_{\lambda}}\cdot\frac{e^{-\mathrm{Fo}^2\cdot K_{\mathrm{a}}}}{\mathrm{erfc}\left(\mathrm{Fo}\cdot\sqrt{K_{\mathrm{a}}}\right)}\approx\sqrt{\pi}\cdot\mathrm{Ko}\cdot\mathrm{Fo} \tag{1}$$

where:

μ_n - root of transcendental equation,

t_{ok} - ambient temperature [°C],

t^0 - temperature in time $\tau = 0$, initial condition [°C],

Fo - Fourier's criterion [1],

Bi - Blot's criterion [1],

Ko - Kossovic's criterion [1],

Θ_{k} - temperature criterion [1],

$K_{\mathrm{a}}, K_{\lambda}$ - constant of similar [1].

Numeical methods

Numerical methods, depending on the nature of the discretization of variables, have significant potential for application in terms of computer modeling. For the typical repeatability of the method are simple algebraic operations. Let's get the final solution to the problem of discrete points (nodes) of the selected differential networks or finite elements, and throughout the region. They can be divided into:

a) **finite element methods** (MKP, FEM),

b) **finite difference methods** (MKD, FDM),

c) **finite volume methods** (MKO, FVM),

d) **border element methods – border integrals** (MHP, BEM),

e) **divide element methods** (MOE, DEM),

f) **Control Volume Methods** (CVM) a **Collocation Methods** (CM).

Methods f) are a special group of finite elements. The most common problems found in the thermal finite difference (finite difference method in explicit, implicit, or combined form) and the finite element method, finite volume, then in particular in the modeling of gas flow in furnace systems. Figure 1 shows the discretization solved the most commonly used methods, finite difference and finite element method. The problem of explicit finite difference method is a numerical stability of solution.

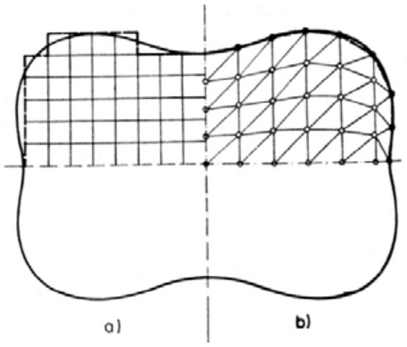


Fig. 1 a) FDM-method, b) FEM-method

2 TEMPERATURE FIELD OF CASTED BLLET

Kinetics of transient temperature field describes the Fourier partial differential equations. If it is necessary to describe the temperature field of a moving billet, must be counted in the transverse direction with a casting velocity v_z in from the classical Fourier equation and the equation passes the Fourier - Kirchhoff - see equation (2).

$$\frac{\mathrm{D}t}{\mathrm{d}\tau} = a \cdot \nabla^2 t + \frac{q_V}{c_p \cdot \rho} \tag{2}$$

where:

t - temperature $[\mathrm{°C}]$,

τ - time $[\mathrm{s}]$,

a - temperature conductivity coefficient $\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right]$,

∇^2 - Laplace transformation operator $\left[\frac{1}{\mathrm{m}^2}\right]$,

c_p - specific thermal capacity by constant pressure $\left[\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}}\right]$,

ρ - density $\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$,

q_V - yield of internal volume thermal source $\left[\frac{\mathrm{W}}{\mathrm{m}^3}\right]$.

After differentiation, differential equations (2) can be obtained from the following form of Fourier-Kirchhoff equation - see equation (3)

$$i_0^+ - i_0 = \frac{\Delta\tau}{\Delta V}\cdot\left[\frac{\sum_{i=1}^{6} P_{k,i}}{\rho} + \Delta S\cdot v_z\cdot\left(i_6 - i_0\right)\right] \tag{3}$$

where:

i_0 - specific enthalpy in time τ $\left[\frac{\mathrm{J}}{\mathrm{kg}}\right]$,

i_0^+ - specific enthalpy in time $\tau + \Delta\tau$ $\left[\frac{\mathrm{J}}{\mathrm{kg}}\right]$,

i_6 - specific enthalpy in vertical direction (in direction of casting velocity) $\left[\frac{\mathrm{J}}{\mathrm{kg}}\right]$,

$P_{k,i}$ - heat fluxes in separate directions of axes system $[\mathrm{W}]$,

$\Delta\tau$ - time step $[\mathrm{s}]$,

ΔV - elementary volume $[\mathrm{m}^3]$,

ΔS - elementary square $[\mathrm{m}^2]$.

To solve the 3D temperature field by a method of networks is generated by the billet method, referred to in Figure 2 Computational grid is fixed, moving the material flowing through the network. The circular billet, there are five types of elements

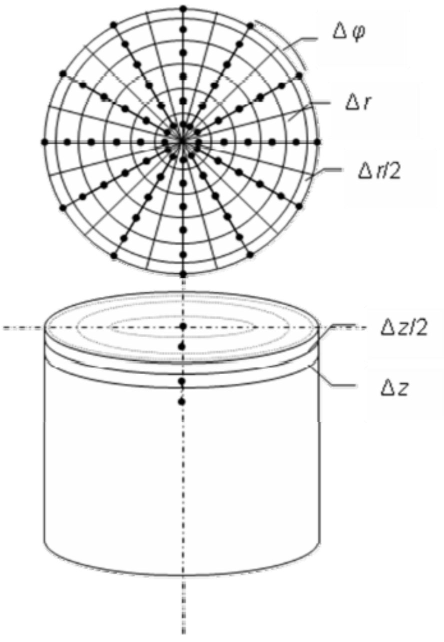


Fig. 2 Net of round billet

- ***internal* elements**,
- ***external* (circuit) elements**,
- ***axis* elements**,
- ***axis external* elements**,
- ***border* elements**.

When calculating the temperature field is the correct choice of conditions essential uniqueness of the solution, the conditions of geometric, physical, and initial surface. Geometric condition is unknown, because it follows a particular form of cast billets (round, rectangular shape), the initial condition is related to the temperature of steel in the tundish. Physical conditions include thermal conductivity, specific heat capacity and density of steel.

Surface conditions can be summed up in dealing with two types. Condition II. species (Neumann), in which it is known heat flux density q. This situation is characteristic of heat in the primary cooling zone

$$-\lambda \cdot \frac{\partial T}{\partial x} = q \qquad \left(\mathrm{W.m^{-2}}\right) \tag{3}$$

where:

q - heat flux density $\left[\frac{\mathrm{W}}{\mathrm{m^2}}\right]$.

Condition III. type (Fourier), in which it is known heat transfer coefficient α. For this condition is characterized by secondary and tertiary zone CCM

$$-\lambda \cdot \frac{\partial T}{\partial x} = \alpha \cdot \left(T_{\mathrm{pov}} - T_{\mathrm{ok}}\right) \qquad \left(\mathrm{W.m^{-2}}\right) \tag{4}$$

where:

α - heat transfer coefficient $\left[\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}}\right]$.

Alternatively, it´s possible to apply a condition that comes from the Stefan - Boltzmann Law, which is crucial for radiation in the form of squares of the thermodynamic functions fourth billet surface temperature and ambient atmosphere

$$-\lambda \cdot \frac{\partial T}{\partial x} = \sigma_0 \cdot \varepsilon \cdot \left(T_{\mathrm{pov}}^4 - T_{\mathrm{ok}}^4\right) \qquad \left(\mathrm{W.m^{-2}}\right) \tag{5}$$

where:

ε - emissivity $[1]$,

σ_0 - Stefan – Boltzmann constant ~ $5{,}67.10^{-8}$ $\left[\frac{\mathrm{W}}{\mathrm{m^2 \cdot K^4}}\right]$.

Typical heat flux density distribution along the height of the mould is given in Figure 3, an example of the relative distribution of heat transfer by cooling the nozzle in Figure 4.

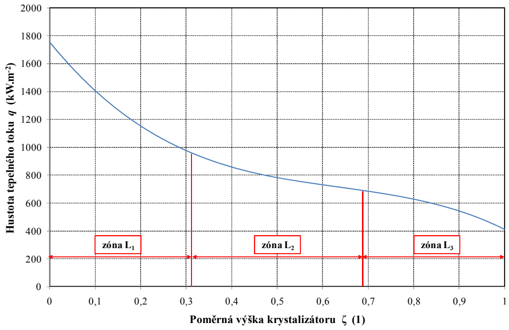


Fig. 3 Typical dependence of heat flux density on the height of mould

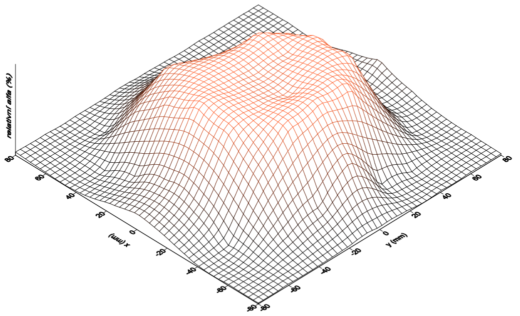


Fig. 4 For example, the relative distribution of heat transfer coefficient on wire-washer area

3 PHYSICAL PROPERTIES OF SIMULATED STEELS

For simulation on the PC were selected following representatives routinely casted steel. The measure of choosing was the amount of carbon. According to its steel content were divided into low-carbon steel (w_C <0,2%), high-carbon steel (w_C > 0,4%) and medium-carbon steel within this range, while steel has been divided into functional groups (2 , 3 and 5) - see Tables 1 and 2.

Tab. 1 Distribution of steel into functional groups

C (%) **Mn/S (%)**	**C < 0,10**	**0,10 < C < 0,20**	**0,20 < C < 0,54**	**0,54 < C < 0,90**
0 < Mn/S < 25	6	5	2	3
Mn/S > 25	6	1	2	3

Tab. 2 Distribution of steel according to carbon content

Type of steel	**Label of steel**	**Group of steel**	**Number of melt**	**Carbon content (%)**
Low-carbon	1059 OCEL A	5	49944	0,140
	4627 ZF1KL	5	51170	0,167
	2057 OCEL C	5	57912	0,170
Medium-carbon	4697 RS355JOK	2	49844	0,240
High-carbon	3188 R73	2	49845	0,492
	3184 R81	2	57938	0,537
	3196 R7VAL	3	55901	0,556
	6314 14109-PK	3	50048	0,976

Solidus and liquidus temperatures, which indicate the boundary between liquid and solid (or doughy) phase can be detected by measuring either the experimental or empirical relations of various authors. For optimal values of these temperatures is advisable to collect patterns and get them using arithmetic average, median or mean.

4 SIMULATION SOLUTIONS OF SOFTWARE TEFIS

This chapter summarizes the results of computer simulations for the above, ordinary cast steel grades, which are represented by a different proportion of carbon. Thorough analysis of the impact of the chemical composition of steel, steel, and the influence of overheating fluctuation level of steel in the crystallizer on the resulting parameters are presented in particular:

- metallurgical length L_m,
- length of liquid phase (core) L_{tek},
- surface temperature of billet during outlet of mould $t_{v,kr}$,
- surface temperature of billet during outlet of secondary cooling zone $t_{v,sek}$,
- casting crust thickness ξ.

In examining the influence of one parameter of the relevant technology, however, is necessary to keep all the other technological parameters at constant values. For example, when examining the effect of casting speed on the metallurgical length, the length of the liquid phase, the surface temperature of billet, cast or thick crust, it is necessary to set a constant water level in the steel mould and constant overheating of the steel. Diagram solution procedure is presented in Table 3 In totals it is necessary for detailed analysis of one brand of steel to make 28 simulations.

Tab. 3 The basic scheme of the procedure of simulation solutions

The examined technological parameter	**Constant technological parameter (YES/NO)**			
	Steel level in the mould **h (%)**	**Casting speed** **v_z (m.min^{-1})**	**Overheating** **$\Delta t_{př}$ (°C)**	**Water flow in the secondary zone**
Effect of steel level	**NO**	**YES**	**YES**	**YES**
	studied the effect	0,5 m.min^{-1}	25 °C	
Effect of casting speed	**YES**	**NO**	**YES**	**YES**
	50 %	***studied the effect***	25 °C	
Effect of steel overheating	**YES**	**YES**	**NO**	**YES**
	50 %	0,5 m.min^{-1}	***studied the effect***	

Cooling water flow in the secondary cooling zone of CCM, for all steel grades and in all cases set to a constant value. The following survey results are presented only for the influence of casting speed for low-and high-carbon steel.

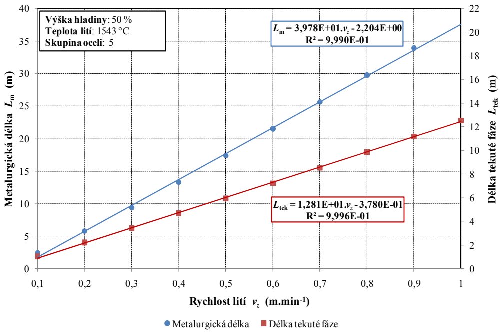
4.1 Effect of casting speed

One of the most important technological parameters in continuous casting steel is casting speed, which is defined in general terms such as speed, leaving the billet mould. The value of the casting speed is associated with dimensions of cast billets, steel types and the type of mould. Low values of casting speed caused by a longer stay billet in the mould, thereby increasing surface temperatures and occur in parallel to increase the local density of heat flow. Higher values of surface temperatures to slow down shrinkage and enabling improved contact with the wall of the billet mould. In contrast, excessive increase in casting speed in order to maximize the overall efficiency of production casting equipment is not appropriate, since this procedure may result in higher occurrence of surface and subsurface defects or cracks.

4.2 Parameters of the simulation process for the influence of casting speed

Simulate the constant overheating of the steel liquidus temperature $\Delta t_{př} = 25$ °C, constant steel level in the mould, $h = 50\%$, and the constant flow rate of cooling water in the secondary. Casting speed is increased from 0.1 m.min^{-1} to 1.0 m.min^{-1} with step of 0.1 m.min^{-1}. The range of casting speeds of 0.3 to 0.7 m.min^{-1} was a step for calculating the thickness of the casting crust soften 0.05 m.min^{-1}, because in this range are more likely to move in casting speed in real-CCM for casting round large wire diameters.

a) Effect of casting speed on the metallurgical length and the length of liquid core



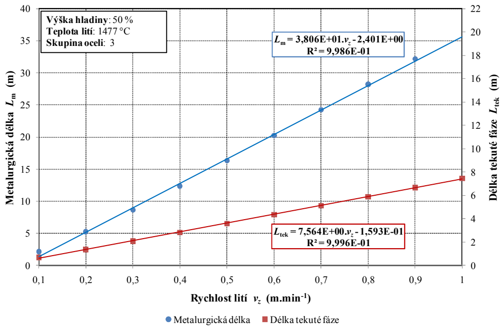
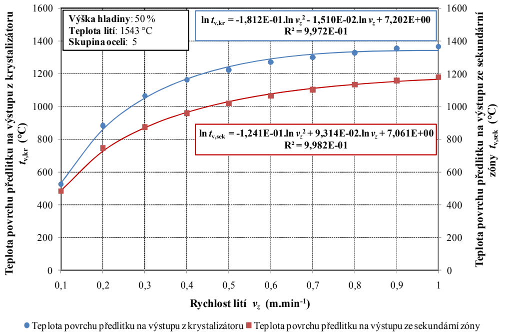


Fig. 5 Change the metallurgical length for different casting speeds - low-carbon steel

Fig. 6 Change the metallurgical length for different casting speeds - high-carbon steel

b) Effect of casting speed on the billet surface temperature at the outlet of primary and secondary cooling zone



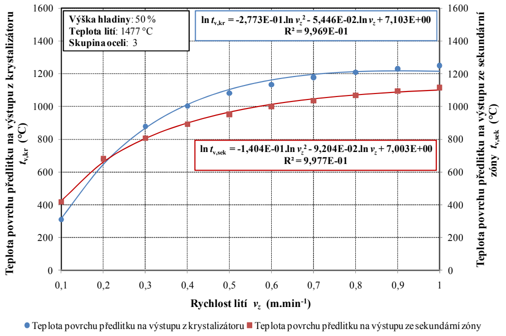
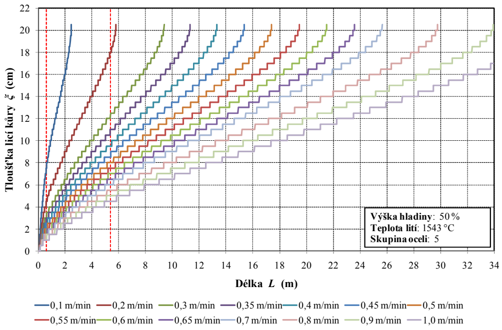


Fig. 7 The temperature change of billet casting for different speeds - low-carbon steel

Fig. 8 The temperature change of billet casting for different speeds - high-carbon steel

c) Effect of casting speed on the casting crust thickness



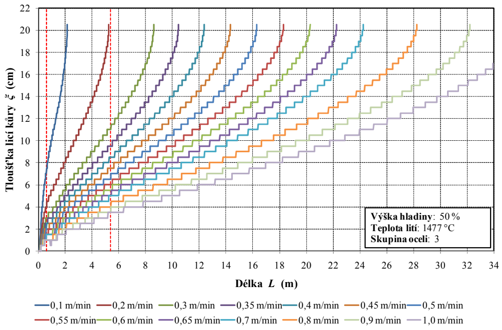


Fig. 9 The increase in thickness of the casting crust for different casting speeds - low-carbon steel

Fig. 10 The increase in thickness of the casting crust for different casting speeds - high-carbon steel

4.3 Discussion of results - sensitivity analysis of the influence of casting speed on the metallurgical length and the length of the liquid phase

Again, sensitivity analysis was performed because of different values of casting speed on the metallurgical length and the length of the liquid phase for the above steel. Among the numerous literary sources from different authors can assume a strong dependence on the length of casting speeds. Methodology of the sensitivity analysis was analogous to the impact level of steel in the crystallizer. As a basis for calculating the value of each gate length and the metallurgical length of time for the liquid phase of casting speed 0.5 m.min^{-1}, which is again shown in bold in the table with gray background.

Tab. 4 Sensitivity analysis of the different casting speed on the metallurgical length and the length of the liquid phase

Steel	**Casting speed (m.min^{-1})**	**Metallurgical length (m)**	**Length of liquid phase (m)**	**Percentage change in metallurgical length (%)**	**Percentage change in the length of the liquid phase (%)**
1059 OCEL A $w_C = 0,140$ %	0,1	2,45	1,04	-85,91	-82,52
	0,2	5,78	2,21	-66,76	-62,86
	0,3	9,37	3,43	-46,12	-42,35
	0,4	13,31	4,68	-23,46	-21,34
	0,5	**17,39**	**5,95**	**0,00**	**0,00**
	0,6	21,51	7,24	23,69	21,68
	0,7	25,64	8,54	47,44	43,53
	0,8	29,78	9,86	71,25	65,71
	0,9	33,93	11,19	95,11	88,07
	1,0	-	12,54	-	110,76
6314 14109-PK $w_C = 0,976$ %	0,1	2,15	0,69	-86,81	-80,73
	0,2	5,25	1,36	-67,79	-62,01
	0,3	8,62	2,08	-47,12	-41,90
	0,4	12,37	2,82	-24,11	-21,23
	0,5	**16,30**	**3,58**	**0,00**	**0,00**
	0,6	20,27	4,34	24,36	21,23
	0,7	24,25	5,12	48,77	43,02
	0,8	28,23	5,89	73,19	64,53
	0,9	32,21	6,67	97,61	86,31
	1,0	-	7,46	-	108,38

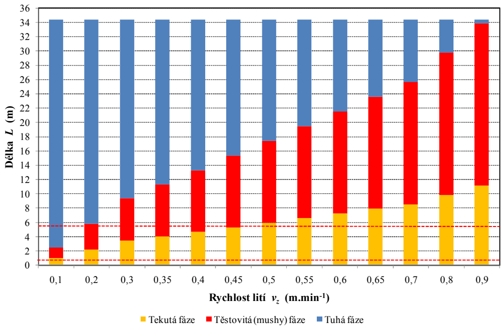


Fig. 11 The length of each phase (liquid, mushy, solid) for casting low-carbon steel

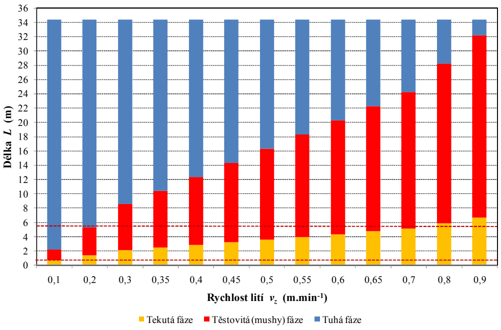


Fig. 12 The length of each phase (liquid, mushy, solid) for casting high-carbon steel

The simulations can be observed that in the case study the effect of casting speed on the metallurgical length and the length of the liquid phase is clearly confirmed by the strong linear relationship which best describes the high value of the regression equations. For metallurgical length of the member acquires the values from $3.7.10^1$ – $3.97.10^{-1}$ for the length of liquid core $9.46.10^0$ – $1.68.10^1$. Practically, this means that the increase / decrease in casting speed of 0.1 m.min^{-1} causes a change in the metallurgical length on average ± 25%, the length of the liquid core of ± 21%.

The largest increase of both metallurgical length and the length of liquid core can be seen in high-carbon steel 6314 14109-PK, in which the percentage increase in the length of the speed of 0.5 m.min^{-1} on the rate of 0.9 m.min^{-1} was 97.61 % and 87.31 %, an increase of the value of the metallurgical length of 16.30 m to 32.21 m and increase the length of liquid core, then the value of 3.58 m to 6.67 m. The relatively little change of these values are showed low-carbon steel in 1059 STEEL A.

4.4 Discussion of results - sensitivity analysis of the change of casting speed on the billet surface temperature at the outlet of the primary and secondary cooling zone

Parameters for sensitivity analysis examining the impact of a case of casting speed on the billet surface temperature at the end of primary and secondary zones were set up in the same manner as described in the preceding paragraphs. The base value of the gate surface temperature at the outlet of the primary $t_{v,kr}$, or the secondary cooling zone $t_{v,sek}$, for the casting speed 0.5 m.min^{-1}, which is color coded for clarity.

Tab. 5 Sensitivity analysis of the different casting speed on the billet surface temperature at the outlet of the primary and secondary cooling zone

Steel	**Casting speed (m.min^{-1})**	**$t_{v,kr}$ (°C)**	**$t_{v,sek}$ (°C)**	**Percentage change $t_{v,kr}$ (%)**	**Percentage change $t_{v,sek}$ (%)**
1059 OCEL A w_C = 0,140 %	0,1	524,42	482,15	-57,15	-52,71
	0,2	883,84	746,18	-27,78	-26,81
	0,3	1064,60	873,96	-13,01	-14,28
	0,4	1162,18	959,08	-5,04	-5,93
	0,5	**1223,84**	**1019,55**	**0,00**	**0,00**
	0,6	1271,36	1065,79	3,88	4,53
	0,7	1299,93	1102,74	6,22	8,16
	0,8	1328,41	1133,06	8,55	11,13
	0,9	1354,55	1158,59	10,68	13,64
	1,0	1366,74	1180,54	11,68	15,79
6314 14109-PK w_C = 0,976 %	0,1	310,0	417,0	-71,33	-56,22
	0,2	678,7	680,6	-37,22	-28,54
	0,3	879,4	805,8	-18,66	-15,39
	0,4	1002,4	891,1	-7,28	-6,43
	0,5	**1081,2**	**952,3**	**0,00**	**0,00**
	0,6	1133,7	999,0	4,86	4,90
	0,7	1177,8	1036,4	8,94	8,83
	0,8	1209,1	1067,2	11,83	12,06
	0,9	1230,5	1093,4	13,81	14,81
	1,0	1249,7	1116,1	15,58	17,20

From the simulations the influence of casting speed on the billet surface temperature at the end of primary and secondary cooling zone is confirmed as the analysis of the influence of different level in the mould, a finding that strongly influenced the speed of casting billet surface temperature at the outlet of the mould.

The highest relative change of temperature has a high-carbon steel - for extreme casting speed of 1.0 m.min^{-1} reflects this change, compared with a rate of 0.5 m.min^{-1} 15.58 % and 17.20 %, while the highest absolute amounts of low-carbon steel, where the extreme rate of 1.0 m.min^{-1} is the temperature at the end of the mould 1366 °C and at the end of the secondary zone of 1180 °C.

It is evident that these temperatures are not affected by casting speed, but the particular chemical composition of cast steel, in particular, the solidus and liquidus temperatures. With a growing proportion of mass of carbon in liquid steel and solid liquidus temperature decreases, so the obvious trend of higher temperatures in the low-carbon steels for the same or other technological parameters.

4.5 Discussion of results - sensitivity analysis of the change of casting speed on the casting crust formation

Similar to the analysis evaluated the impact of changes in the level of steel casting mould for the production of bark, to evaluate the parameter of casting speed. Therefore simulated in the range of casting speeds of 0.1 m.min^{-1} to 1.0 m.min^{-1}, ie. including extreme values. Step 0.1 m.min^{-1} was chosen, only m.min interval 0.3 to 0.7 m.min^{-1} was refinement to 0.05 m.min^{-1}. The level of steel in the mould was 50 % and overheating of the steel above the liquidus temperature of 25 °C.

Tab. 6 The values of the constants *K* and *n* for different casting speeds

Casting speed (m.min^{-1})	**w_C = 0,140 %**		**w_C = 0,976 %**	
	K **(1)**	***n*** **(1)**	***K*** **(1)**	***n*** **(1)**
0,10	0,2088	0,6136	0,2400	0,6055
0,20	0,1933	0,6103	0,2398	0,6042
0,30	0,1894	0,6065	0,2220	0,5979
0,35	0,1866	0,6056	0,2175	0,5930
0,40	0,1847	0,6045	0,2143	0,5917
0,45	0,1827	0,6040	0,2121	0,5903
0,50	0,1810	0,6035	0,2098	0,5894
0,55	0,1797	0,6032	0,2076	0,5889
0,60	0,1788	0,6027	0,2063	0,5881
0,65	0,1781	0,6023	0,2052	0,5875
0,70	0,1775	0,6019	0,2046	0,5868
0,80	0,1767	0,6012	0,2042	0,5861
0,90	0,1763	0,6005	0,2038	0,5849

The values of the constants *K* and *n* to change the case casting speeds become substantially more variance than the simulations at different heights in the steel mould. From Table 6 it is possible to draw different conclusions:

a) The constant value with increasing casting speed in the same type of steel are reduced

b) The value of power n is also constant with increasing casting speed in the same type of steel are reduced, but less strongly,

c) With respect to carbon content in steel, toward the higher values to the constant upward trend, while the power law constant n shows the opposite trend.

Casting speed up to 0.2 m.min^{-1} is not appropriate because the stiff wire to complete the entire section is already in the secondary cooling zone with increasing carbon content, this problem is even worse. Also, increasing the casting speed of 0.8 m.min^{-1} is not desirable because the billet is not able to cross over to his exit from the die casting machine perfectly solidification - see speed casting 1.0 m.min^{-1}. For the evaluation of the casting crust thickness, depending on casting speed and time setting, use multiple regression analysis in Microsoft Excel 2007. This time was chosen because of the logarithmic dependence of high levels of reliability (Determination) R^2 ~ 0.95 in all groups studied steels. The resulting empirical formula is summarized in the following table.

Tab. 7 Overview of empirical equations casting bark thickness for all the simulated steel - dependence on the casting speed

Steel label	Power law equation casting crust thickness ζ (cm)
1059 OCEL A **w_C = 0,140 %**	$\xi = \left(-1{,}468 \cdot 10^{-2} \cdot \ln v_z + 1{,}719 \cdot 10^{-1}\right) \cdot \tau^{\left(-6{,}083 \cdot 10^{-3} \cdot \ln v_z + 5{,}995 \cdot 10^{-1}\right)}$
4627 ZF1KL **w_C = 0,167 %**	$\xi = \left(-1{,}456 \cdot 10^{-2} \cdot \ln v_z + 1{,}765 \cdot 10^{-1}\right) \cdot \tau^{\left(-6{,}950 \cdot 10^{-3} \cdot \ln v_z + 5{,}961 \cdot 10^{-1}\right)}$
2057 OCEL C **w_C = 0,170 %**	$\xi = \left(-1{,}520 \cdot 10^{-2} \cdot \ln v_z + 1{,}765 \cdot 10^{-1}\right) \cdot \tau^{\left(-6{,}532 \cdot 10^{-3} \cdot \ln v_z + 5{,}968 \cdot 10^{-1}\right)}$
4697 RS355JOK **w_C = 0,240 %**	$\xi = \left(-1{,}541 \cdot 10^{-2} \cdot \ln v_z + 1{,}786 \cdot 10^{-1}\right) \cdot \tau^{\left(-6{,}762 \cdot 10^{-3} \cdot \ln v_z + 5{,}949 \cdot 10^{-1}\right)}$
3188 R73 **w_C = 0,492 %**	$\xi = \left(-1{,}606 \cdot 10^{-2} \cdot \ln v_z + 1{,}901 \cdot 10^{-1}\right) \cdot \tau^{\left(-7{,}646 \cdot 10^{-3} \cdot \ln v_z + 5{,}889 \cdot 10^{-1}\right)}$
3184 R81 **w_C = 0,537 %**	$\xi = \left(-1{,}551 \cdot 10^{-2} \cdot \ln v_z + 1{,}931 \cdot 10^{-1}\right) \cdot \tau^{\left(-7{,}586 \cdot 10^{-3} \cdot \ln v_z + 5{,}878 \cdot 10^{-1}\right)}$
3196 R7VAL **w_C = 0,556 %**	$\xi = \left(-1{,}491 \cdot 10^{-2} \cdot \ln v_z + 1{,}932 \cdot 10^{-1}\right) \cdot \tau^{\left(-7{,}129 \cdot 10^{-3} \cdot \ln v_z + 5{,}875 \cdot 10^{-1}\right)}$
6314 14109-PK **w_C = 0,976 %**	$\xi = \left(-1{,}651 \cdot 10^{-2} \cdot \ln v_z + 1{,}979 \cdot 10^{-1}\right) \cdot \tau^{\left(-9{,}188 \cdot 10^{-3} \cdot \ln v_z + 5{,}826 \cdot 10^{-1}\right)}$

5 CONCLUSION

This paper deals with the problem of numerical simulations of temperature field in a round billet (410 mm), with continuous casting steel casting machine operation. Optimal configuration of the thermal regime casting machine significantly affects the quality molded products, which is closely linked with economic indicators of the production. The processes involved in cooling and solidification of billet to its physical nature in the complex phenomena of heat transfer and mass transfer. To solve these tasks in general, are treated, increasingly, the simulations on powerful computers through software packages. The problem is shifting to the field of numerical modeling, where for practical use can be considered finite difference method (FDM) and finite element method (FEM). The effectiveness of these methods, but is largely associated with the precision of the description of processes occurring in the steel at high temperatures, the main emphasis is on identifying surface and physical conditions.

Many domestic but also foreign artists, describes the kinetics of continuously cast billets, usually through the Fourier´s partial differential equations and the influence of convection together with the casting speed included in the value of the equivalent thermal conductivity. In this thesis, by contrast, assumes that the solidification and cooling of the billet is consistent with the Fourier´s-Kirchhoff´s equation, which reflects the speed of the moving billet. The aim of this study was to create a comprehensive mathematical framework for creating software simulation, but also, through him, to make a number of simulations routinely cast steel grades in order to find a correlation between technological parameters, composition and quality of cast steel production.

The main computational algorithm to solve the thermal field moving billet was chosen explicit finite difference method (finite difference method) when the appropriate differential equations are transformed into a set of differential equations. An integral part of the developed software - Tefis is also an algorithm to determine the stability of numerical solutions for non-compliance with this condition in the calculation leads to divergence and disintegration.

Great attention should be paid to the conditions under which differential equations are generally applicable. These conditions make up the uniqueness conditions task, which is possible in classical concepts, divided into initial, geometry, physics and surface. Start and geometrical conditions resulting from the assignment task is to determine the physical problem and surface conditions. The Department of Thermal Engineering Technical University of Ostrava, the surface conditions determined partly on the basis of physical modeling of the so-called cold and hot model when the effect of secondary cooling water jets through examining the filament probe, but also through experimental measurements on real casting machines. Determining the physical conditions based on the work of G. Wölk.

To simulate the environment of the software were selected Tefis eight heats of the characteristics of the carbon content from 0.140 % to 0.976 % three groups of steels 2, 3, and 5 According to the carbon content of steel can be divided into low-carbon (up to 0.170% w_C), medium-carbon (from 0.170 % to 0.492 % w_C) and high-carbon (above 0.492 %). Simulate the effect of water level in the steel mould, the influence of different casting speed, secondary cooling effect and the effect of overheating of steel above the liquidus temperature on the overall temperature field of a round format, which was presented by the metallurgical length, the length of the liquid phase, the surface temperature of the billet output of primary and secondary cooling zone and the thickness of crust generated casting. Evaluation of the results was based on sensitivity analysis, which examined the value base and took it for one set of simulated data are analyzed and the absolute percentage deviation.

The simulations showed that if the influence of different height levels in the steel mould virtually no effect on the metallurgical length and length of the liquid phase (change in the tenths, units maximum per cent), as well as in the case of surface temperature at the end of primary and secondary zone there significant changes. The relatively small value of the regression lines for casting thick bark indicates a weak influence of this parameter to its creation. For different values of overheating of steel showed significantly greater effect of technological parameters on the length of the liquid phase than the metallurgical length. Increasing the superheat temperature of 40 °C above the liquidus temperature caused the extension of the metallurgical length by an average of 3 %, but the length of the liquid phase increased up to 20 %, while the billet surface temperature at the outlet of the primary and secondary cooling zone will rise by 3 %. The higher value of overheating of steel are reflected in the cooling curves, which increases with overheating curves "shift" to greater lengths. Casting speed proved to be the most important variable that affects virtually all parameters of the casting. The simulations revealed that the change of casting speed has a strong linear character of the length of liquid core and a metallurgical length, which can be documented by the high value of the directives in the regression equations of lines. Change speed casting of 0.1 $m.min^{-1}$ extend to or shorten the length of metallurgical by 25 % and length of liquid core by an average of 21 %. Significantly change the response speed of casting surface temperature of billet at the end of primary and secondary zone, and, thanks to the logarithmic dependence, particularly in the casting speed of 0.5 $m.min^{-1}$. A strong dependence is also apparent in the case of casting thickness crust. Lower speed billet casting cause congealing in a shorter time period than in the case of higher speeds, when the blank non-solidification throughout its cross section or end of the tertiary zone.

In general we can say that computer simulations allow defining the optimal parameters of continuous casting of steel. Using the results obtained in the computer simulation gives very high economic benefits, leading to a reduction in the number of technology trials along with an optimization process of continuous casting of steel.

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Grant number	Title	Year of solution	Main researcher
MPO, FT-TA4/048	Research conditions and create a model of chemical inhomogeneities, stress and failure of materials in continuous casting of steel	2007 - 2010	René Pyszko
GA ČR, 106/07/0938	Research of heat transport during the cooling of hot surfaces with water nozzles	2007 - 2010	Miroslav Příhoda
GA ČR, 106/08/P150	Thermal processes in the mould during continuous casting of steel	2008 - 2010	Marek Velička

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