NON-STATIONARY BOUNDARY CONDITIONS IN THERMAL MODELS OF CONTINUOUS CASTING

PYSZKO René[1], PŘÍHODA Miroslav[1], FRANĚK Zdeněk[2], VELIČKA Marek[1], BURDA Jiří[1]

[1]*VŠB - Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering, Ostrava, Czech Republic, EU*

[2]*Silesian University in Opava, School of Business Administration in Karvina, Opava, Czech republic, EU*

Abstract

The article focuses on the issue of boundary conditions for simulations of non-steady states in continuous casting machines. Numerical models of the temperature field of the continuously cast strand based on the finite difference method were implemented in off-line and on-line versions. The correctness of the simulation depends on the accuracy of the boundary conditions. Their determination is a technically demanding and costly procedure. From operational data, only approximate boundary conditions can typically be obtained; often average values in time or in space rather than the detailed local and immediate values. Modelling of unsteady behaviour of the casting process is therefore characterized by uncertainty. The boundary condition in the mould can be determined by means of measuring temperatures directly in the mould wall using thermocouples. However, it is demanding to keep greater number of sensors installed permanently. The boundary condition in the secondary cooling area is based on the measurement of heat transfer coefficient by means of the laboratory physical model. Significant complication is caused by non-linearity of heat transfer coefficient in the secondary cooling area due to the Leidenfrost phenomenon. Two reasons of the boundary conditions time variations can be distinguished. The first are deterministic, induced by the operator's changes of casting and cooling parameters, the second are random or quasiperiodic changes, caused by spontaneous fluctuations of parameters and internal quantities.

Keywords: Continuous casting, modelling, boundary conditions, Leidenfrost temperature

1. INTRODUCTION

Continuous casting of steel is currently the dominant technology used for liquid steel processing into solid billets, blooms or slabs. Continuous casting comprises simultaneous acting of thermal, mechanical and chemical processes in three zones of cooling in the casting machine. The mould is considered as a primary zone, where the solid shell of the strand is formed while heat is being removed through the mould walls. In the secondary zone the strand is cooled mainly by water spraying and in the tertiary zone it is cooled by natural convection and radiation. Although at constant casting parameters the technology seems to the external observer to be a steady continuous process, in fact it is a dynamic transient process with characteristic fluctuations. Knowledge of the state of the fluctuating process is a precondition for the process control to achieve a quality and defect-free product. Modern continuous casting machines (CCM) are often equipped with process monitoring systems featuring a breakout and quality prediction as well as numerical models functioning as software sensors of the strand solidification and cooling [1]. The main task of the numerical models is to calculate the strand temperature field and shell thickness. It requires immediate values of boundary conditions in all three cooling zones. Even the best models give just as good results as accurate boundary conditions they receive. As it is almost impossible to obtain ideally detailed and exact boundary conditions, the results of the numerical model cannot be considered as absolutely accurate and uncertainty of results should be taken into account. The paper shows some causes of fluctuations of parameters and quantities in time and space, difficulties of the boundary conditions determination and mechanisms how they influence simulation results.

2. NUMERICAL MODELS OF THE STRAND TEMPERATURE FIELD

Thermal numerical models operate as software sensors for detecting the strand temperature field, solid shell thickness, metallurgical length etc. The model “Tefis”, which was developed at VŠB - Technical University Ostrava, Department of thermal engineering, was implemented as on-line version at the machine for casting round blocks and as two off-line versions of square and round billets. The temperature field kinetics of the solidifying strand can be described by the Fourier-Kirchhoff equation

$$\frac{\mathrm{D}t}{\mathrm{d}\tau} = a \cdot \nabla^2 t + \frac{q_V}{c_p \cdot \rho} \quad (\mathrm{K \cdot s^{-1}}) \tag{1}$$

where a ($m^2 \cdot s^{-1}$) is thermal diffusivity of steel, q_V ($W \cdot m^{-3}$) is volumetric internal heat source, c_p ($J \cdot kg^{-1} \cdot K^{-1}$) is specific heat, ρ ($kg \cdot m^{-3}$) is density and $\frac{\mathrm{D}t}{\mathrm{d}\tau}$ is a substantial derivative of temperature by time.

The algorithm of the model is based on numerical solving the equation (1) using the explicit version of the finite difference method. The calculated bulk extends from the steel level in the mould down to the end of the strand at the cutting mechanism. The elements of the 3D mesh have the shape either of a cube or a cylinder sector, according to the coordinate system.

3. STATIC DEPENDENCE OF BOUNDARY CONDITIONS ON PARAMETERS AND QUANTITIES

Solving the numerical problem requires knowledge of boundary conditions that are usually classified to initial, geometrical, physical and surface kinds. The initial condition represents the temperature field of all elements at the beginning of the solution. Geometrical conditions include strand transversal dimensions, length, casting arc radius and steel level in the mould. Physical conditions encompass thermo-physical parameters of steel depending on temperature. Surface conditions describe the intensity of heat removal from each boundary element (conditions of the 2nd kind is used at the contact of steel with the mould [2], the 3rd kind is used in the secondary and tertiary zones) or temperature (the condition of the 1st kind is used in the elements on the steel level in the mould). Precision and physical correctness of the simulation results depend on the accuracy of the boundary conditions.

Surface and physical boundary conditions depend on values of casting parameters, in particular on the steel level in the mould, the casting speed, steel chemical composition and temperature, cooling water temperature, pressure and flow rate into nozzles in the secondary cooling zone etc. Boundary conditions also depend on internal quantities in the caster, such as mould oscillating curve, mould dimensions, mould wear, friction in the mould, powder layer thickness, gas gap thickness in the mould, local surface temperature of the strand, strand vibrations etc. Some of these quantities are measurable by special monitoring and diagnostics systems, many others are unknown. The dependence can be described by the formula

$$B_i = f\left(P_1, P_2, \ldots P_n, x_1, x_2, \ldots x_m\right) \tag{2}$$

where B_i is i^{th} boundary condition, P_1 - P_n are casting parameters and x_1 - x_m are relevant internal quantities. There are two sources of the boundary condition uncertainty: The first one is inaccuracy of values of casting parameters and internal quantities and the second is the uncertainty of the function f which is generally complex, nonlinear and in some cases stochastic.

The best example of nonlinear boundary condition is heat transfer coefficient (HTC, α) under cooling nozzles in the secondary zone, which depends on strand surface temperature and water pressure. The dependence was measured by the original laboratory equipment developed at the Department of thermal engineering, VŠB - Technical University Ostrava [3]. The apparatus consists of the heated sensor for measuring heat flux and the industrial robot for moving the nozzle relative to the sensor. The apparatus measures heat transfer coefficient using an indirect method which is based on solving an inverse problem of heat conduction while temperatures of the sensor stainless steel core are recorded during cooling the sensor by spraying water. **Figure 1** shows how measured HTC depended on surface temperature in case of the nozzle JATO 3065 for three values of water pressure while the sensor was situated directly in the nozzle axis at the distance of 100 mm from the nozzle.

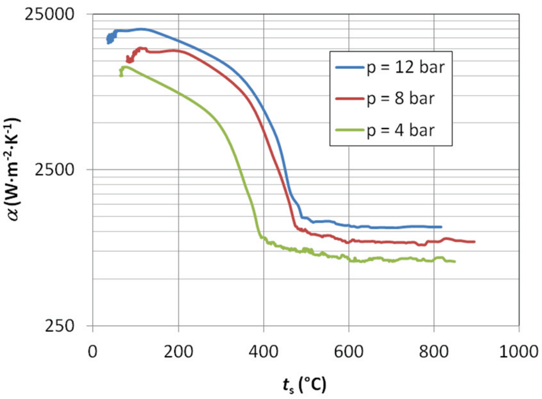

Figure 1 Heat transfer coefficient for different pressures of cooling water

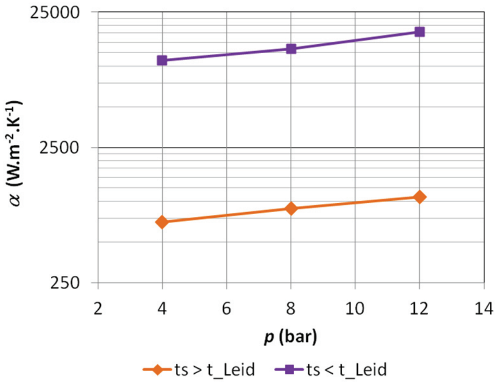

Figure 2 Average values of HTC above and below the Leidenfrost temperature

The nonlinearity of the curves in **Figure 1** was caused by the Leidenfrost phenomenon. In reality, the Leidenfrost temperature was not constant but it shifted to higher temperature with the rise of water pressure or flow rate.

In numerical models of continuous casting, often the dependence of average HTC on water pressure is implemented. **Figure 2** shows two characteristics of average HTC for the nozzle JATO 3065 at surface temperatures above and below the Leidenfrost temperature (t_Leid), which were measured at three values of water pressure. Mostly only a function for surface temperatures above the Leidenfrost temperature is used in models, but in case of intensive cooling the characteristics should smoothly switch to the other curve when surface temperature gets bellow the Leidenfrost point.

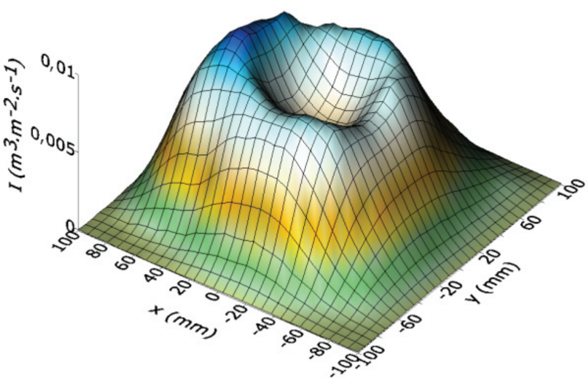

Figure 3 Measured distribution of spray intensity of the cone nozzle

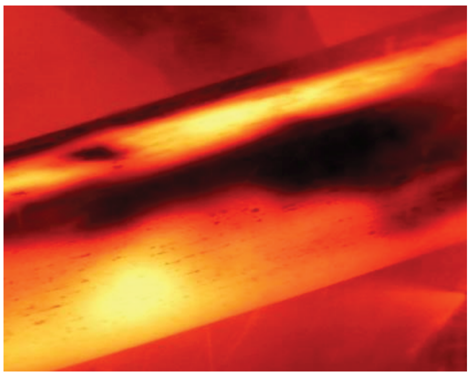

Figure 4 Surface of the real billet with uneven temperature field

The boundary condition in the form of HTC has a significant impact on the simulation results. The Leidenfrost temperature depends, apart from surface temperature and water pressure, also on size and kinetic energy of water drops, surface roughness, oxides layer thickness [4 - 7] etc. Moreover, as each point of the strand surface has different temperature, oscillation marks depth, oxides layer thickness and as spray intensity varies on the surface (see measured nozzle water distribution in **Figure 3**), the surface boundary condition is uncertain and the cooling process is unstable. It often results in a non-homogeneous temperature field similar to the case of the square billet in **Figure 4**. To obtain such detailed simulation results is unlikely.

4. NON-STACIONARY BOUNDARY CONDITIONS

Non-stationary character of boundary conditions is caused by time changes of both casting parameters and internal quantities. Two reasons of time variations can be distinguished - deterministic and spontaneous.

4.1. Deterministic changes of parameters and quantities

The most influential parameter is casting speed. Deterministic changes induced by the operator or by the caster control system concurrently influences cooling water flow rate, mould oscillation frequency etc. **Figure 5** shows the record of casting speed and metallurgical length calculated by the on-line numerical model "Tefis" during 18 hours of casting the round block. The accuracy of the results depends on the knowledge of the effects of casting speed on quantities and consequently on the boundary conditions.

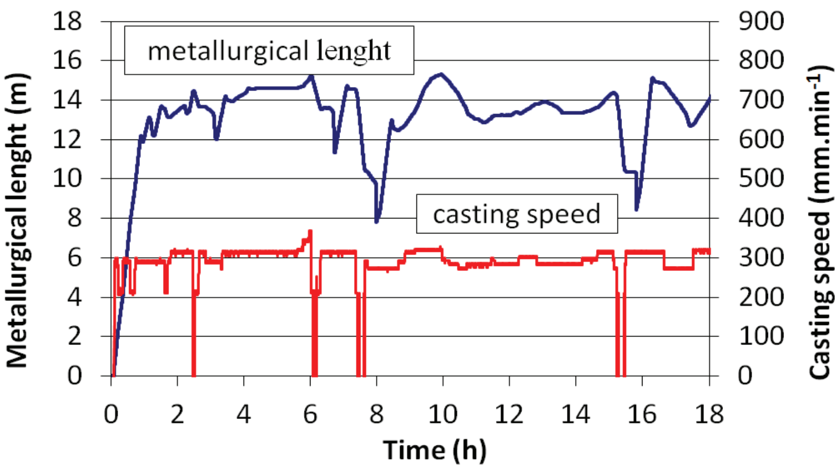

Figure 5 Simulation of metallurgical length by the on-line model

4.2. Spontaneous changes of parameters and quantities

Interdependencies among parameters and quantities make the problem more complicated. Nonlinear mechanical and thermal bonds in the system can cause instability and formation of spontaneous oscillations after even a negligible change of the selected parameter. Therefore the system often exhibits quasi-periodic, stochastic or chaotic behaviour [8] that is impossible to replicate by a model due to a lack of detailed boundary conditions. According to the variable and the level of the caster instrumentation, the fluctuations of quantities are either measurable or hidden.

Figure 6 shows time courses of the temperature measured in the mould wall in the position of 250 mm below the mould upper edge, billet surface temperature (P2) measured at the position of 3.7 m from the mould bottom edge and steel level in the mould. Oscillations of these quantities have similar frequency spectrum and, according to cross-correlation analysis, seem to be caused by variation of steel level in the mould. **Figure 7** shows strand surface temperatures measured by three optical sensors P1 - P3 in locations of 1.15 m (P1), 3.7 m (P2) and 16.7 m (P3) from the bottom edge of the mould. Higher amplitude of the signal from the temperature sensor P2 in comparison to P1 is unexpected and it demonstrates the system instability. It is supposed that the amplification of the strand surface temperature oscillation in the secondary zone was caused by the non-linearity of boundary condition due to the Leidenfrost phenomenon.

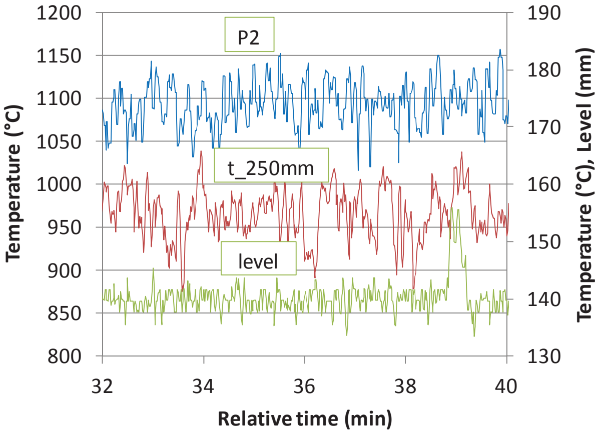

Figure 6 Mould wall temperature, strand surface temperature and steel level

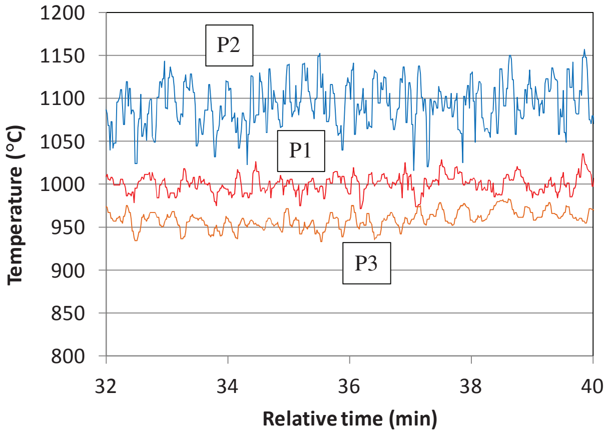

Figure 7 Strand surface temperatures measured by three sensors P1 - P3

Strands also feature spatial fluctuations of quantities in the direction perpendicular to the vector of withdrawal, both circumferentially and inwardly. Spatial variations of quantities in the real caster can result in an uneven thickness of the solid shell, variable solid phase structure etc. An example of the uneven shell thickness is shown in **Figure 8**.

Time fluctuation of the particular quantity, which acts at the certain position in the casting machine, is projected as a longitudinal and transverse spatial fluctuation in a moving strand. See the considerable longitudinal temperature oscillation of the billet in **Figure 9** [9]. For the purpose of data evaluation, it is necessary to take into account the position where each quantity operates, and also considerable traffic delays in the system. Before processing, data were transformed from the database of time series to the database of samples belonging to the series of strand cross sections.

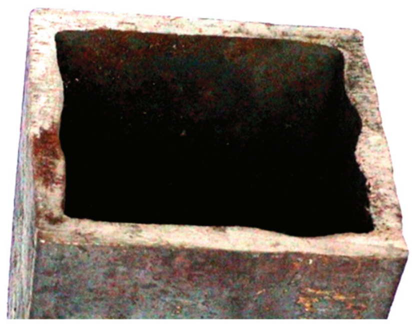

Figure 8 Solid shell with uneven thickness after breakout

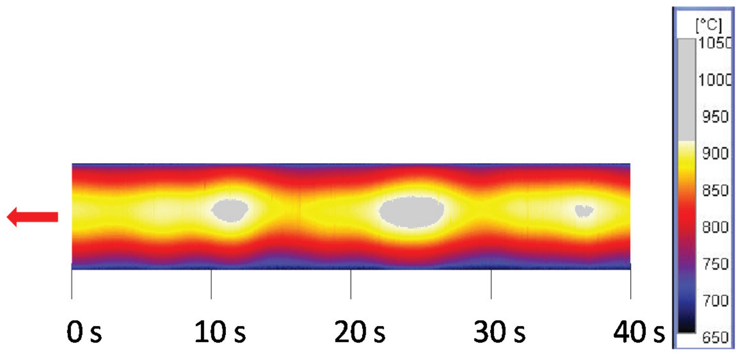

Figure 9 Oscillation of longitudinal surface temperature of the billet measured by optical temperature scanner

The quantities sometimes vary by more than 50 % from the mean value in time and space. Abilities of today's hardware and software make numerical models, both detailed differential [10] and simplified [11], capable to simulate thermal problems, as well as coupled thermal-stress problems with flowing and solidification, but the sensitivity to unknown and variable boundary conditions is so high that the results may be far from reality without a thorough verification of the model.

5. CONCLUSION

The article discusses the influences of parameters on the unsteadiness and inaccuracy of the boundary conditions and attempts to draw attention to the consequent uncertainty of the simulation results that can significantly deviate from reality. The more detailed results are required, the higher is their uncertainty. In the system of continuous casting, the boundary conditions depend on a number of parameters and internal quantities, some of which are not technically measurable. The dependences are generally complex, nonlinear and in some cases stochastic. Spontaneous oscillations are generated due to interdependencies among the parameters and quantities. As an example, the nonlinear dependence of heat transfer coefficient under the cooling nozzle on the strand surface temperature often results in a strand non-homogeneous temperature field and, under certain circumstances, amplification of the strand surface temperature oscillations in the secondary cooling zone.

ACKNOWLEDGEMENTS

The authors are grateful to companies Třinecké železárny, a.s., ArcelorMittal Ostrava a.s. and DASFOS, v.o.s. for their cooperation during operational measurings. This paper originated with the support of grants MPO No. FT-TA4/048, GAČR No. GA106/07/0938, SP2016/110 and SP2016/103.

REFERENCES

[1] ŠTĚTINA, J., KLIMEŠ, L., MAUDER, T., KAVIČKA, F. Final-structure prediction of continuously cast billets. *Materiali in tehnologije*, 2012, vol. 46, no. 2, pp. 155-160.

[2] PYSZKO, R., PŘÍHODA, M., VELIČKA, M. Method for determining the thermal boundary condition in the CC mould for numeric models. In *METAL 2010: 19th International Conference on Metallurgy and Materials.* Ostrava: TANGER, 2010. 7 p.

[3] PYSZKO, R., PŘÍHODA, M., BURDA, J., FOJTÍK, P., KUBÍN, T., VACULÍK, M., VELIČKA, M., ČARNOGURSKÁ, M. Cooling nozzles characteristics for numerical models of continuous casting. *Metalurgija,* 2013, vol. 52, no. 4, pp. 437-440.

[4] PATRICK, B., BARBER, B., BROWN, D. Practical aspects of the design, operation and performance of caster spray systems. *La Revuede Métallurgie-CIT*, 2001, pp. 383-390.

[5] WENDELSTORF, R., SPITZER, K. H., WENDELSTORF, J. Effect of oxide layers on spray water cooling heat transfer at high surface temperatures. *International Journal of Heat and Mass Transfer*, 2008, vol. 51, no.19-20, pp. 4892-4901.

[6] WENDELSTORF, J., SPITZER, K, H., WENDELSTORF, R. Spray water cooling heat transfer at high temperatures and liquid mass fluxes. *International Journal of Heat and Mass Transfer*, 2008, vol. 51, no. 19-20, pp. 4902-4910.

[7] HORSKÝ, J., HRABOVSKÝ, J., RAUDENSKÝ, M. Impact of the oxide scale on spray cooling intensity. In HEFAT 2014: *10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*. Orlando, Florida, 2014, pp. 1480-1485.

[8] LEE, P. D., RAMIREZ-LOPEZ, P. E., MILLS, K. C., SANTILLANA, B. Review: The "butterfly effect in continuous casting. *Ironmaking and Steelmaking*, 2012, vol. 39, no. 4, pp. 244-253.

[9] KUBĚNA, J., CIBULKA, J., HERMANN, R., MICHALEK, K. Irregular Solidification of Continuously Cast Billets (in Czech). *Hutnické listy*, 2009, no. 5, pp. 19-23.

[10] ŠTĚTINA, J., MAUDER, T., KLIMEŠ, L., KAVIČKA, F. Minimization of surface defects by increasing the surface temperature during the straightening of a continuously cast slab. *Materiali in tehnologije*, 2013, vol. 47, no. 3, pp. 311-316.

[11] ŠPIČKA, I., HEGER, M. Utilization mathematical and physical models derived therefrom real-time models for the optimization of heating processes. *Archives of metallurgy and materials*, 2013, vol. 58, no. 3, pp. 981-985.