Transactions on Modelling and Simulation vol 27, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

Heat transfer under an air-water cooling jet

F. Kavicka[1], J. Stetina[1], B. Sekanina[1], B. Velicka[2] & R. Ramik[1]
[1]*Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic.*
[2]*VUHZ a.s., Dobra, Czech Republic*

Abstract

The solidification and cooling of a continuously cast billet, slab or cylinder—generally a concasting—and the simultaneous heating of the crystallizer is a very complicated problem of three-dimensional (3D) transient heat and mass transfer. The solving of such a problem is impossible without numerical models of the temperature field of the concasting while it is being processed through the concasting machine (CCM). An important part of the CCM is the so-called secondary-cooling zone, which is subdivided into thirteen sections—the first section engages water jets from all sides of the concasting and the remaining twelve engage air-water cooling jets positioned only above the upper and beneath the underside of the concasting.

Experimental research and measurements have to take place simultaneously with numerical computation, not only to be confronted with the numerical model but also to make it more accurate throughout the process. Experimentation has also been conducted on a laboratory device simulating a concasting surface, in order to determine the intensity of the cooling jets, all of which had been measured individually on the actual laboratory device. These coefficients are the main input data of the numerical model of the temperature field, which serves also to determine the effect of radiation.

This analysis was conducted using a program devised within the framework of the GA CR projects no. 106/98/0296 and 106/99/0728, of the EUREKA project EU-CONMOD 1867 and of the COST-OC.P3.20.

Transactions on Modelling and Simulation vol 27, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

1 Introduction

One of the more significant differences between a concasting machine (CCM) for the casting of billets and that for the casting of slabs (Figure 1) is in the cooling within the secondary-cooling zone. This is due to the convection of a greater amount of heat from the voluminous slab casting, where the secondary-cooling zone is subdivided into thirteen sections. The first section engages water jets from all sides of the concasting. The remaining twelve sections engage air-water cooling jets, which are positioned only on the upper and underside of the concasting. It is therefore very important to determine the correct boundary conditions for the numerical model of the temperature field.

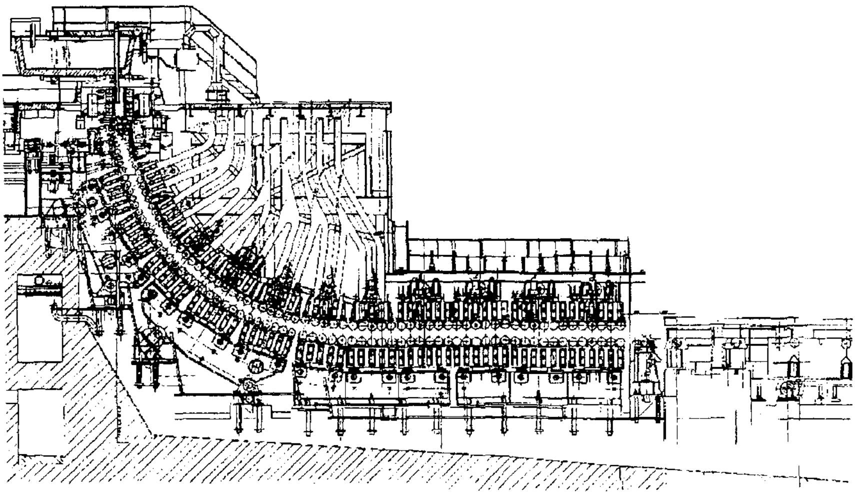

Figure 1: A concasting machine (CCM)

2 An original numerical model of the temperature field of a slab

The solidification and cooling of a concasting and simultaneous heating of the crystallizer is a very complicated problem of 3D transient heat and mass transfer. The 3D transient temperature field of the concasting, passing through the CCM (the zones of zero, primary, secondary and tertiary cooling), can be described by the Fourier-Kirchhoff equation

$$\frac{\partial T}{\partial \tau} = \frac{\lambda}{\rho \cdot c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \left(w_x \frac{\partial T}{\partial x} + w_y \frac{\partial T}{\partial y} + w_z \frac{\partial T}{\partial z}\right) + \frac{Q_{SOURCE}}{\rho \cdot c} \quad (1)$$

The derivation of the temperature by time becomes zero upon the reaching of the steady state. Equation (1), when considering movement in the direction of the z-axis only, can be simplified to

Transactions on Modelling and Simulation vol 27, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

$$\frac{\partial T}{\partial \tau} = a.\Delta T + w_z \frac{\partial T}{\partial z} + \frac{Q_{SOURCE}}{\rho \cdot c} \qquad (2)$$

The 3D transient temperature field of a crystallizer cooled by water is expressed by the Fourier equation, i.e. equation (2) without the member $w_z(\partial T/\partial z)$.

The authors had chosen the explicit difference method, which enables the application of the most convenient method of numerical simulation of the release of latent heat of phase or structural changes using the thermodynamic enthalpy function.

In order to describe the temperature field of a concasting in all its three stages, i.e. in:

the melt → the mushy zone → the solid phase

equation (2) must be converted to

$$\frac{\partial i_V}{\partial \tau} = \lambda\, \Delta T + w_Z \frac{\partial i_V}{\partial z} + Q_{SOURCE} \qquad (3)$$

The specific volume enthalpy $i_v = c.\rho.T$ is dependent on temperature. The specific heat capacity c, density ρ and heat conductivity λ are also functions of temperature.

The authors have developed (and published [1-3]) an original numerical model, which solves the Fourier and Fourier-Kirchhoff equation.

If the general nodal point is positioned within the wall of the crystallizer, then its unknown temperature in time $\tau+\Delta\tau$ is given by the explicit formula as a function of the temperatures of the same point and all six neighboring points in the previous time step τ. If the general nodal point is positioned within the actual concasting, then the unknown enthalpy in time $\tau+\Delta\tau$ is given by the analogical explicit formula as a function of the enthalpies of the same point and all six neighboring points in the previous time step τ. The temperature is obtained from the functional enthalpy-temperature dependence. This function must be known for the relevant metallic material.

The numerical model provides for the analysis of the temperature field of the concasting as it passes through the zero, primary-, secondary- and tertiary-cooling zones, i.e. through the entire CCM. The computer model enables the analysis of the temperature field of the crystallizer, including the influence of its material, its cooling system, characteristics of the cooling medium, etc. The program also takes into account the non-linearity of the task, i.e.:

- The dependence of the thermophysical properties of all materials entering the system being investigated, and
- The dependence of the heat-transfer coefficients on all boundaries of the system on the temperature of the working surface–of the concasting or crystallizer–and on other influences (e.g. shift rate, intensity of spraying).

The program has a graphical input and output, i.e. automatic generation of the net (for an arbitrary shape of crystallizer and concasting profile). The temperature fields are displayed in the form of color iso-lines, iso-zones and temperature-time curves for any point of the system being investigated. The program is also designed to trigger sub-programs, which take care of the pre-processing part of the program and the actual computation, and then send files containing the results to the post-processing part.

The exactness of the presented numerical model depends not only on the spatial and temporal discretization, but also on the accuracy with which the thermophysical properties of the materials of all parts of the system are determined. This concerns the following properties:

- The heat conductivity λ
- The specific heat capacity c and
- The density ρ

of the cast metal in the solid and liquid phase, the crystallizer and of the casting powders. These properties can be set either via a table or with the help of coefficients of approximation polynomials describing the curve.

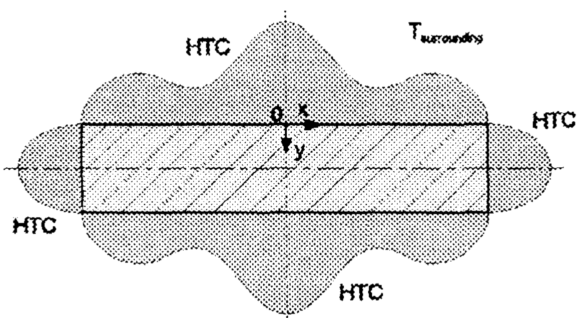

Figure 2: Boundary conditions on the slab surface

Furthermore, the exactness of the numerical model depends on the derivation of boundary conditions. Therefore the setting of the properties is followed by the setting of the boundary conditions, i.e. the values of the heat transfer coefficient (*HTC*) on all CCM boundaries. The dependences of these coefficients on temperature and other operating properties must also be given. The definition of boundary conditions is the most difficult part of the investigation of the thermokinetics of this process.

The boundary conditions of the numerical model of the temperature field of the concasting are defined as the transfer of heat by convection (Figure 2). This *HTC* includes the so-called reduced convection coefficient corresponding to heat transfer by radiation.

The order of the importance of *HTC*s on each boundary has also been settled. In the system comprising the concasting and crystallizer, the order is

1. The *HTC* at the point of contact between the concasting and crystallizer (the influence of a cooling powder has also been included).
2. The *HTC* in the cooling channel.

Transactions on Modelling and Simulation vol 27, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

3. The *HTC* on the lower base of the crystallizer.
4. The *HTC* on the level of the melt and the upper base of the crystallizer.
5. The *HTC* on the outside wall of the crystallizer.

The only, but extremely important, coefficient, after leaving the crystallizer, is the *HTC* on the surface of the concasting, and is mainly dependent on the temperature of the surface, the shift rate and the intensity of spraying. This paper therefore continues with a discussion on heat transfer coefficients under air-water cooling jets, which spray the concasting in the so-called secondary-cooling zone.

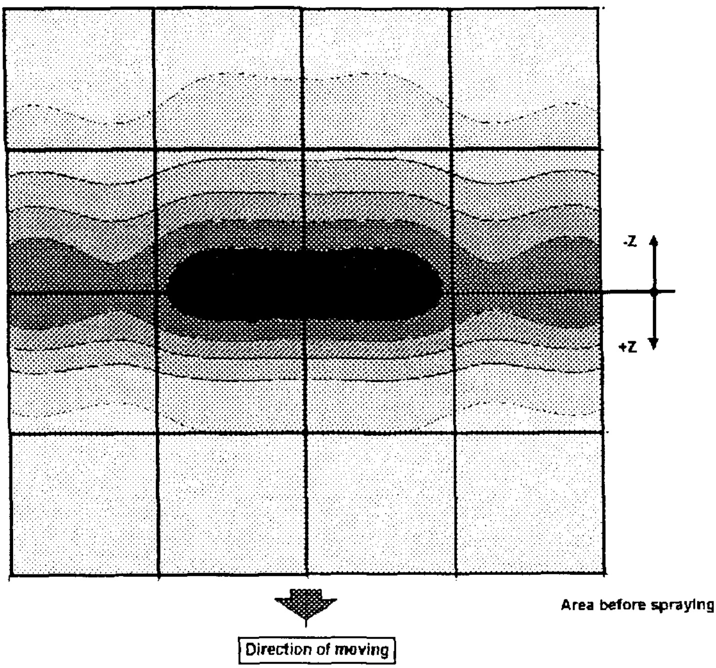

Figure 3: The *HTC* on the slab surface

Regarding the fact that on a real CCM, where there are many types of jets with various settings positioned inside a closed cage, it is practically impossible to conduct measurement of the real boundary conditions. Therefore, a laboratory device was introduced in order to measure the cooling characteristics of the jets. This laboratory device enables the measurement of each jet separately. It comprises a steel plate mounted with 18 thermocouples, heated by an external electric source. The steel plate is heated to the testing temperature, than it is cooled by a cooling jet. On the return move the jet is covered by a deflector, which enables the movement of the jet without cooling the surface.

The laboratory device allows the setting of:

- The jet type.
- The flow of water.
- The air-pressure (of air-water jets).

- The distance between the jet and the investigated surface.
- The surface temperature.
- The shift rate.

Based on the temperatures measured in dependence on time, the *HTC*s are calculated by an inverse task. They are then processed further using an expanded numerical and an identification model and converted to coefficients of the function *HTC(T,y,z)* (Figure 3), which expresses the *HTC* in dependence on the surface temperature, and also the position of the concasting with respect to the jet.

3 Application of the numerical model on a concast steel slab

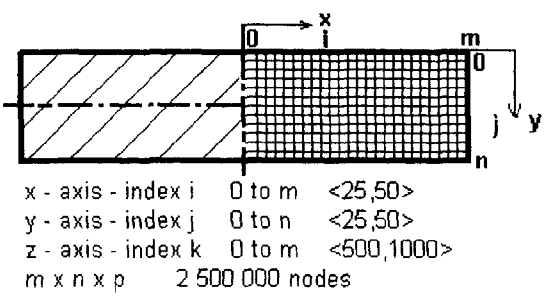

Figure 4: The slab profile and the numerical network

The numerical model described above is applied in order to investigate a concast steel slab with a profile of *a x b* (Figure 4) in any stage of the process, where *a* is the width ranging from 800 to 1600 mm and *b* is the thickness ranging from 120 to 250 mm [4]. A diagram of the longitudinal section of the CCM for radial concasting is illustrated in Figure 1.

It was decided to simulate the temperature field of a 1300x145 mm steel slab. The conditions of pouring were characterized by the temperature in the tundish (1543°C), by the temperature of the liquid (1519°C), by the temperature of the solidus (1479°C), and by the shift rate of the slab (1.3 m.min^{-1}).

The chemical composition of the slab steel (in weight %) is: 0.13% C, 0.26% Mn, 0.50% Si, 0.017% P, 0.08% S, 0.06% Cr, 0.02% Ni, 0.04% Cu and 0.027% Al.

The maximum number of nodal points is 2.5x10^{6} (Figure 4), which could also be sufficient in order to cover a more complex cross section. Such a density of the net enables the linear interpolation of the temperatures among the points of the net, and also among the time sectors.

In order to cover all types of jets and their layouts (incl. their settings) on a specific CCM, it was necessary to conduct 22 experimental measurements. Figure 5 illustrates the courses of the *HTC* of the same jet for two different flows of cooling water.

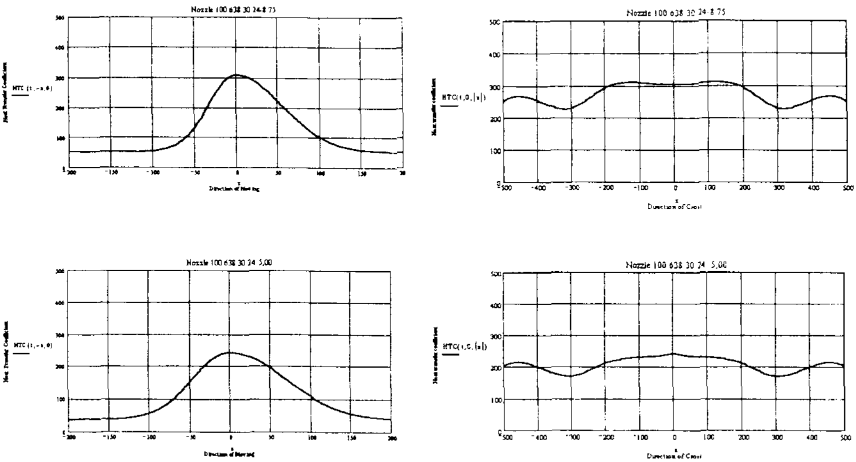

Figure 5: The *HTC* for two different flows of cooling water

Despite the fact that the laboratory device provides a very good basis for numerical modeling of the temperature field of a concasting, it is suitable to expand the experimentation with additional measurements on a real CCM.

Regarding the above-mentioned, the measurements can be conducted only in a limited number of points. Therefore, the position, which affects the quality of the surface of the concasting the most, was selected, i.e. the region closest to the crystallizer—the first section of the secondary-cooling zone. A total of four pyrometers were positioned within the cage (Figure 6). The pyrometers were placed inside a special casing in order to be able to withstand higher temperatures. Furthermore, it is necessary to use compressed air to disperse the

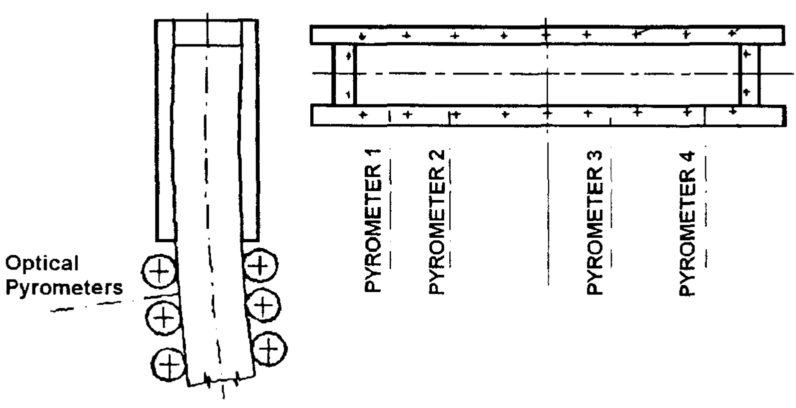

Figure 6: Arrangement of measurement sensors

Transactions on Modelling and Simulation vol 27, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

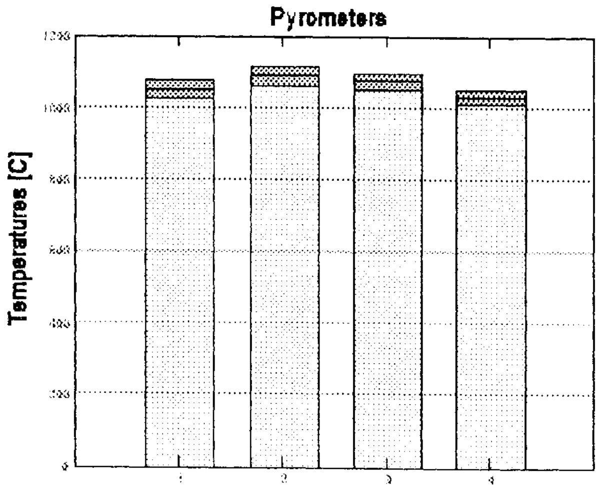

Figure 7: Temperatures measured by pyrometers

arising water vapor, which would otherwise distort the results attained by the optical measurement of the surface temperatures (Figure 7).

The course of the reduced heat transfer coefficient is illustrated in Figure 8. It is obvious that radiance is dependent on the surface temperature.

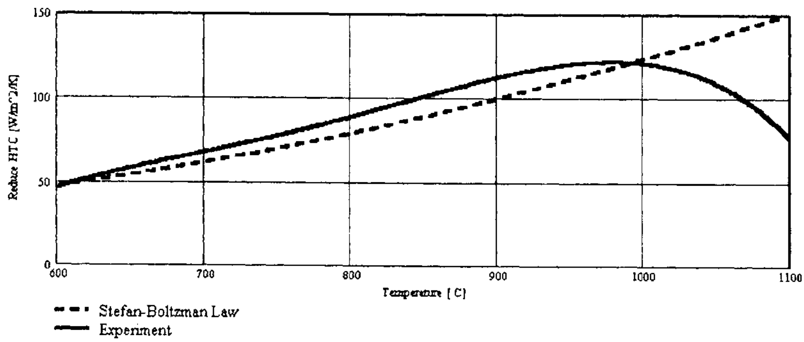

Figure 8: The dependence of the reduced *HTC* on temperature

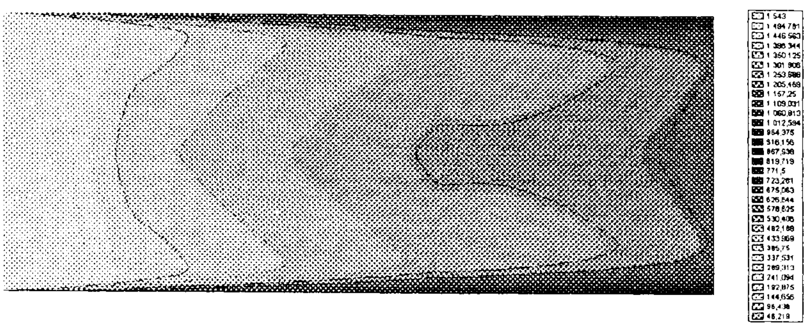

Figure 9: The temperature field of the longitudinal section

Transactions on Modelling and Simulation vol 27, © 2001 WIT Press, www.witpress.com, ISSN 1743-355X

4 Numerical results

A graph containing iso-lines or iso-zones can be displayed or printed whenever necessary (Figure 9). Very useful is the 2D graph in Figure 10, which shows the temperature history in selected points of the cross-section of the slab. The course of the temperature can be displayed in any user-defined point.

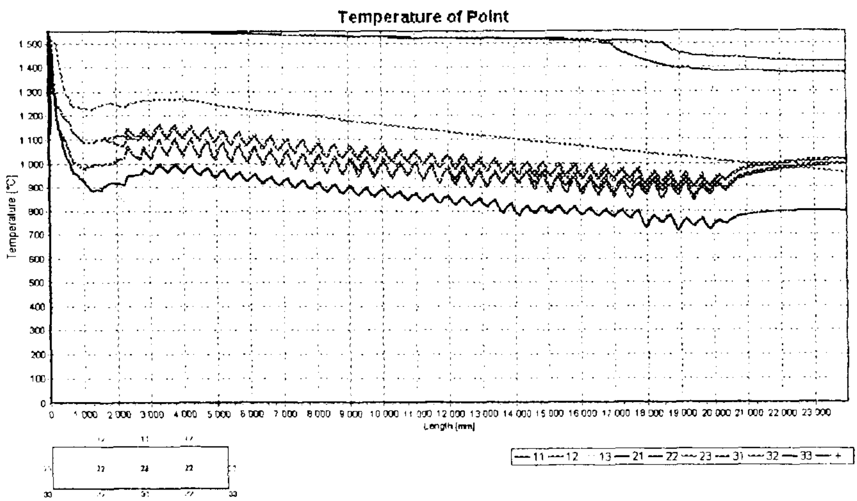

Figure 10 The temperature history in selected points of the cross-section

5 Conclusions

The value of the *HTC* coefficient on the surface of the slab, as it enters the secondary-cooling zone, significantly affects the process simulation from the viewpoint of the temperature field, the technological length, and also other technological properties. It therefore affects prediction of the quality of the slab.

In order to be able to simulate this boundary condition within the numerical model as accurately as possible, it is necessary to conduct experimental measurement on each jet in the secondary-cooling zone individually.

Each of the eight jets had been measured separately on the hot model, on which the hot surface of the slab, which is cooled by a moving jet, can be modeled. The temperatures measured on the surface of the model can be entered into an inverse task to calculate the intensity of spraying, which, in turn, can determine the *HTC* by a special mathematical method.

These values (of the coefficients of all jets), which correspond satisfactorily with experimentally attained temperatures and technological length, have been successfully applied in the calculation of the temperature field of slabs.

Nomenclature

c	specific heat capacity	$[J.kg^{-1}.K^{-1}]$
HTC	heat transfer coefficient	$[W.\ m^{-2}.K^{-1}]$
i_v	specific volume enthalpy $i_v=i.\ \rho$	$[J.m^{-3}]$
λ	heat conductivity	$[W.\ m^{-1}.K^{-1}]$
τ	time	[s]
w_z	shift rate	$[m.s^{-1}]$
x,y,z	axes in given directions	
Q_{SOURCE}	latent heat of the phase or structural change	$[W.m^{-3}]$
V	volume	$[m^3]$
T	temperature	[K]
ρ	density	$[kg.m^{-3}]$
$\Delta\tau$	time step	[s]

References

[1] Kavička F., Hloušek J., Štětina J.. *Analysis of the effect of thermodynamic properties and boundary conditions on the calculation accuracy of solidification thermokinetics.* Proceedings of the 62nd World Foundry Congress, Philadelphia, USA, 1996.

[2] Kavička F.,Brhel J., Sekanina B., Khodadadi J.M.. *Comparison of two Thermal Insulators for a Riser Using Numerical Simulation.* Proceedings of the Julian Szekely Memorial Symposium on Material Processing. Cambridge, Massuchusetts, USA, p.701-710, 1997.

[3] Kavička F., Štětina J., Velička B.. *A Influence of boundary Conditions on Calculation Accuracy of the Temperature Field of a solidified continuously cast Steel Billet.* Proceedings of the 7th International Metallurgical Symposium METAL'98, Ostrava, 1998.

[4] Kavička F., Stránský, K., Štětina,J., Dobrovská,V., Dobrovská,J., Khodadadi J.M.. *Industrial application of two numerical models in concasting technology.* Proceedings of the Conference of the ASME, Boston, USA, p.27-38,1999.

[5] Kavička F., Štětina J.: *A numerical model of heat transfer in a system a plate casting - mold - surroundings for optimization.* Proceedings of the Conference of the ASME, Seattle, USA, July 2000, p.161-168

[6] Kavicka F., Stetina J.. *The influence of thermophysical properties of steels on the numerical simulation of concasting process.* Proceedings of the 22nd International conference on the Boundary element method, Cambridge, UK, September 2000, p.243-252

[7] Kavička F., Štětina J., Sekanina B., Ramík P.: *An original numerical model of heat and mass transfer in a concasting machine.* Proceedings of the 3rd International conference on advances in fluid mechanics AFM 2000, Montreal, Canada, May 2000, p.705-714