Experimental measurement and its irreplaceability for the numerical simulation of temperature fields of technological processes

Frantisek Kavicka[1*], *Jaroslav* Katolicky[1], *Jiri* Hejcik[1], *Ondrej* Pech[1]

[1]Brno University of Technology, Faculty of Mechanical Engineering, Czech Republic

Abstract. Solidification and cooling of the gravitationally cast steels metals or ceramic materials or continuously cast metals rank among the major technological processes. Optimization of these processes is unthinkable without numerical simulation of the non-stationary temperature field during solidification including phase change and cooling. The success of the models is conditioned by knowledge of the thermophysical parameters of all materials entering the casting-mold-surroundings system, as well as knowledge of all initial and boundary conditions of the simulated process at all system boundaries. However, it is also necessary to refine and correct the results of the numerical model by experimental measurements. The importance and benefit of experiments is shown as an example in the numerical optimization of gravity casting of massive castings from steel and ductile cast-iron or material EUCOR as well as in the numerical optimization of continuous casting of a steel slab.

1 Solidification and cooling and its numerical and experimental solutions

Solidification and cooling down of a casting as well as the simultaneous heating of a metal or non-metal mould is a rather complex problem of transient heat and mass transfer. This process in a system casting (riser)-mould (chills)-ambient can be described by the Fourier's equation of 3D transient conduction of heat. 3D transient temperature field of a system of concasting-mould (crystallizer) or concasting-ambient (in so called a concasting machine, shortly a caster) is described by Fourier-Kirchoff's equation. In both equations there is a member expressing latent heat of the phase or structural changes. These equations are solvable only by means of modern numerical methods. However the application of the 3D numerical model on a transient temperature field requires systematic experimentation, including the relevant measurement of the operational parameters directly in the foundry. The results of the measurement (which is focused on measuring temperatures) serve not only to verify the exactness of the model, but also to maintain continuity of the procedure: real process (risering, melting, pouring, solidification, etc.) → input data → numerical analysis

* Corresponding author: kavicka@fme.vutbr.cz

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

→ optimization → correction of real process (risering, melting, pouring, solidification, etc.). Temperature measurement (using thermocouples and pyrometers) and its successive confrontation with the calculation proved that it is possible to apply the numerical model on basic calculations of solidification and cooling of the object [1,2].

2. Examples of numerical and experimental solutions of the temperature field

The numerical model for the simulation of the temperature field of a system casting- mould-ambient was created by ANSYS [3] (see Paragraphs 2,1 to 2.3 and 2.5). The original numerical model BDSM [4] (Brno Dynamic Solidification Model) for the simulation of the temperature field of a caster was developed (see Paragraph 2.4). Results of numerical and experimental research of the temperature field are presented for ductile cast-iron rollers, between which train rails are rolled, for the massive block of ductile cast iron, for the stone –block from special ceramic material EUCOR, for the concast steel billet and for the experimental aluminium ingot.

2.1 Gravitationally cast cylinder of ductile cast iron

Ductile cast-iron rollers, between which train rails (with a hardness of 300 HB and greater) are rolled, are cast into cylindrical iron moulds. It is therefore necessary to find and ensure optimal relationships between the matrix structure and the resultant values of the mechanical properties of the rollers in order to maximize the length of life. The requirements introduced here cannot be met without perfect knowledge of the course of solidification, cooling and heat treatment of the cast rollers as well as the kinetics of the temperature field of the casting and mould [51.
The dimensions of the cylindrical casting and of the iron mould are given in **Fig. 1**, the diameter of the actual roller is 1180 mm and height 2100 mm. This figure illustrates the entire set-up comprising two parts of the sand mould for the upper and lower spindle ends and the iron mould. The working surface of the iron mould is covered with a separating layer – hereafter “separator” (which is a special lubricant applied in various thicknesses to the inside walls of the iron mould and kiln-hardened at 180 °C prior to casting). The initial temperature of the mould was 20 °C. The pouring temperature of the melt was 1336 °C. The casting was performed from underneath with tangential in-flow. The total time of casting of the ductile cast-iron was 175 seconds. The calculation of the temperature field dealt mainly with the effect of the separator between the casting and the iron mould on the solidification of the roller.
Experimental research and temperature measurement must be conducted simultaneously with numerical calculation in order to make the model more accurate and to verify it [6,7]. The distribution of temperatures along the height of the iron mould and roller was measured in three horizontal planes, 100 mm (section I), 1000 mm (section II) and 1950 mm (section III) from the bottom edge of the iron mould (**Fig. 1**). **Fig 2** brings the mesh for numerical model – software pack ANSYS. **Figs. 3 and 4** show a more detailed diagram of the positioning of the hot junction of the thermocouple. The temperatures of the iron mould were taken beneath the inner surface (at depths of 5 and 10 mm) and outer surface (at a depth of 5 mm). The sensors for measuring the temperature of the roller took the temperatures at a depth of 5 mm beneath the surface in the same horizontal planes as the temperatures of the iron mould. The temperature was measured in a total number of 14 points where 3 were on the surface of the roller, 7 on the inner surface of the iron mould and 4 points on the outer surface of the iron mould.

Section III (**Figs. 1, 3 a 4** – detail A and D), where thermocouples recorded the temperatures the longest – specifically point 9 (the inner surface of the iron mould) and point 13 (the outer surface of the iron mould) – had been selected for the comparison of the temperatures from the numerical simulation with the experimentally obtained temperatures from inside the iron mould. The results of this comparison are illustrated in **Figs. 5 and 6**. The interruption of the measurement of the temperatures after 85 hours was caused by the changing of the measurement equipment and, furthermore, the thermocouple in point 13 did not resume work.

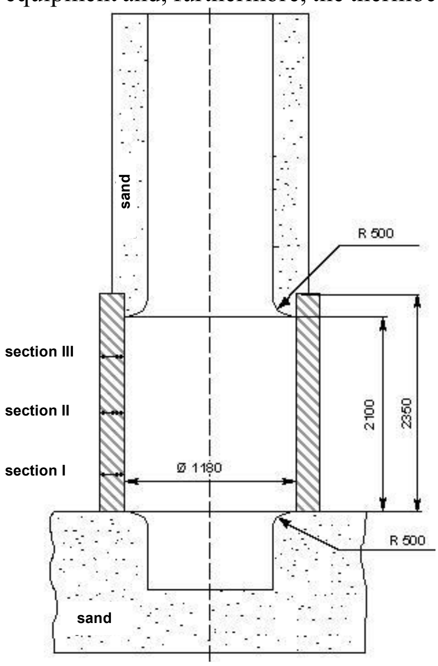

Fig. 1. Schema of a vertically cast roller

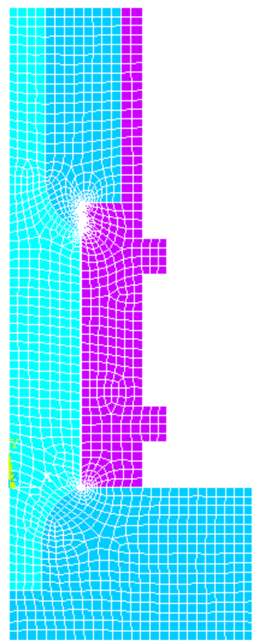

Fig. 2. The mesh for the numerical model of the temperature field

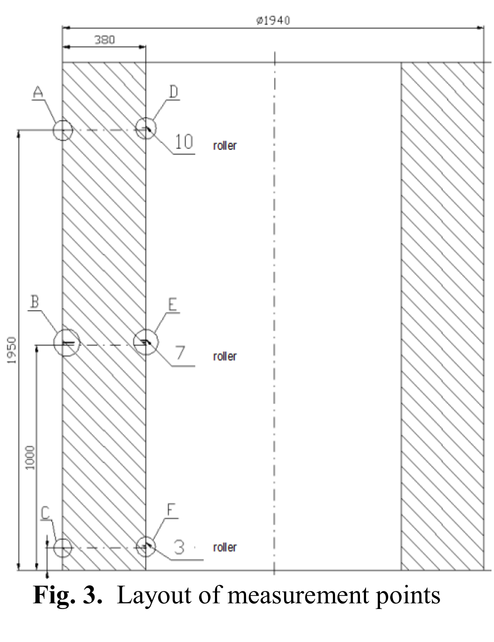

Fig. 3. Layout of measurement points

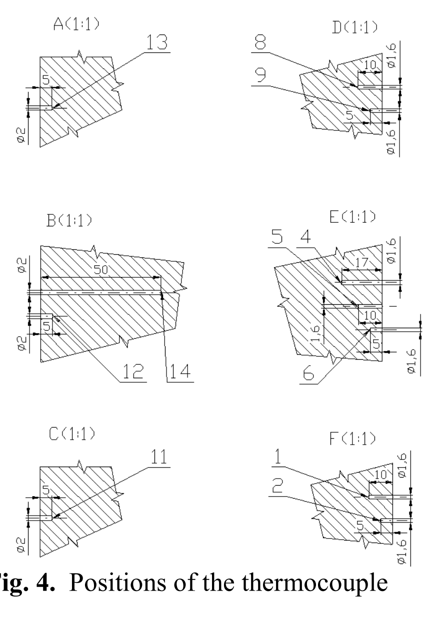

Fig. 4. Positions of the thermocouple

Figures 5 and 6 confirm a very close similarity of the calculated and measured temperatures of the iron mould. It appears that the absolute values and histories of experimental and calculated temperatures in the points of the cylindrical casting and iron mould, which had been selected for comparison, are very similar. The determined relationship between the solidification time (of the entire casting or its geometrical centre) and the thickness of the separator applies. The simulation of the temperature field of the roller and the mould can therefore be considered successful.

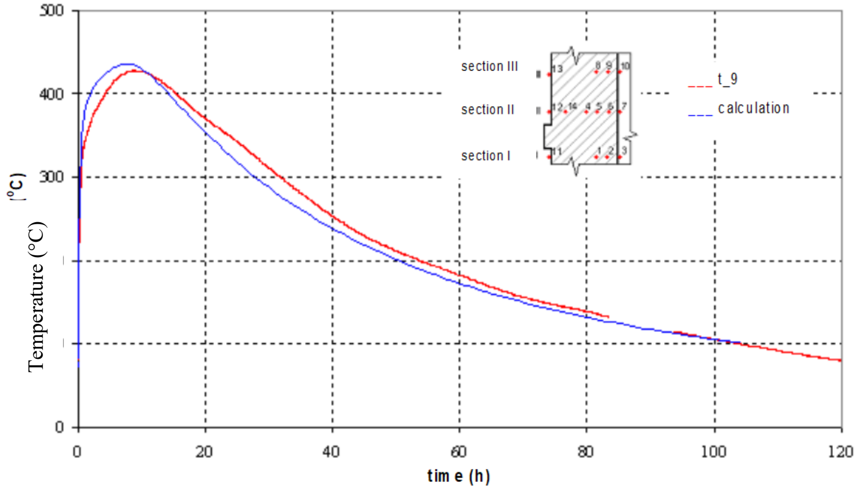

Fig. 5. Calculated versus measured temperatures (**Fig. 4** - point 9)

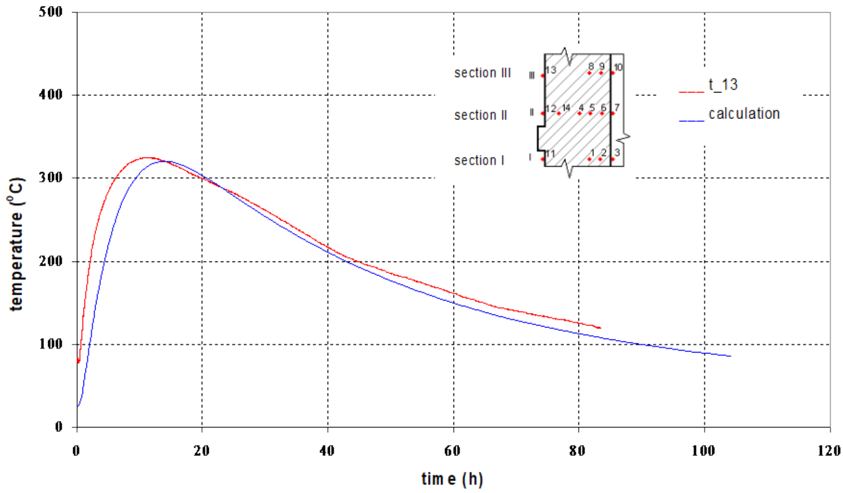

Fig. 6. Calculated versus measured temperatures (**Fig. 4** - point 13)

2.2 Gravitationally cast massive block of ductile cast iron

The quality of a massive casting of cast iron with spheroidal graphite is determined by all the parameters and factors that affect the metallographic process and also others. The centre of focus were not only the purely practical questions relating to metallurgy and foundry technology, but mainly the verification of the possibility of applying two original models –

the 3D model of transient solidification and the cooling and the model of chemical and structural heterogeneity. Both models have only been applied to describing the temperature field, the control of crystallisation and the cooling of the block, to the descriptions of their chemical heterogeneity and to determining the basic characteristics of their microstructure [8]. The success of both models model depends on the accuracy of the temperature field model. In this combination of two models supported by the necessary experiment temperature measurement, it is possible to optimize the technology of pouring cast-iron castings and successive cooling in order to achieve the most convenient structure. This includes a structure created of spheroids of graphite, preferably with as high a density as possible and spread throughout the casting as evenly as possible, with a minimal ratio of particles of graphite marked as degenerated shapes. The results of the measurement serve not only to verify the exactness of the model, but also to already mentioned maintain continuity of the procedure.

A real 500 × 1 000 × 500 mm ductile cast-iron block had been used for the numerical calculation and the experiment. The block was cast into sand moulds with various arrangements of steel chills of cylindrical shape. For example the molding of the block with chills on one side shows **Fig. 7**, which brings also the mesh for ANSYS [9].

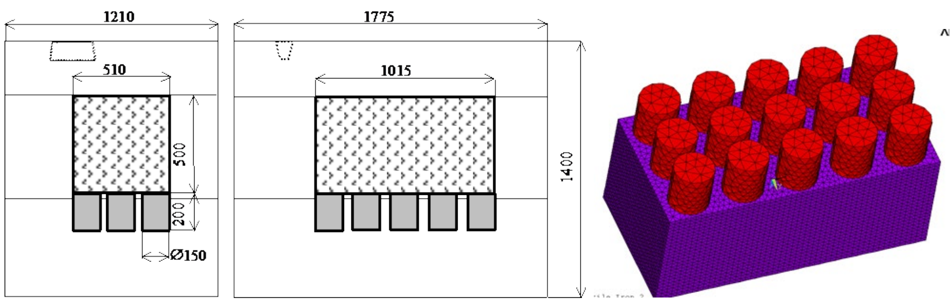

Fig. 7. The moulding of the block with chills on one side and the proposal of computational mesh

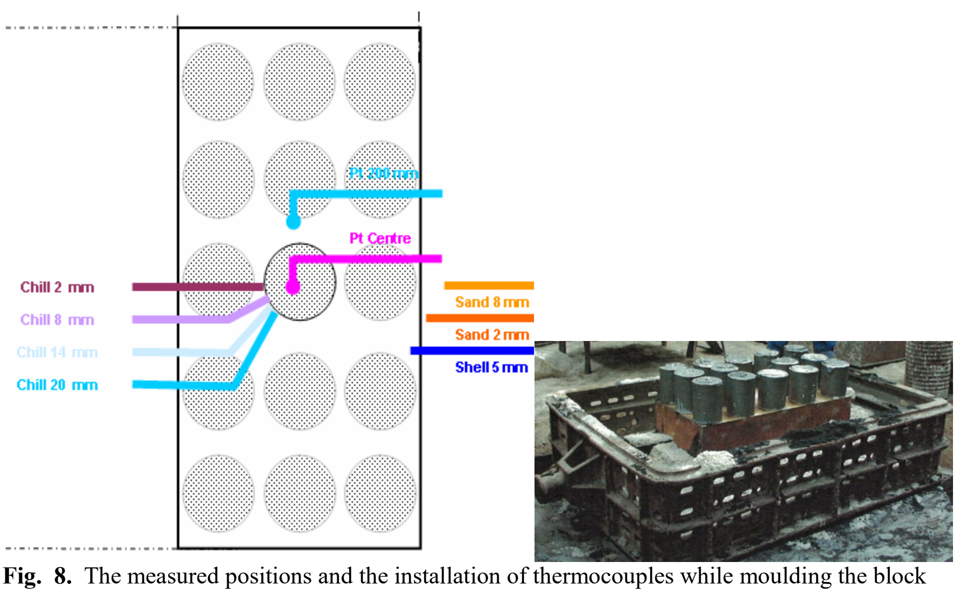

Fig. 8. The measured positions and the installation of thermocouples while moulding the block with chills on one side

Temperature measurement [10] (using thermocouples) and its successive confrontation with the calculation proved that it is possible to apply the numerical model on basic calculations of solidification and cooling of the casting. It is also possible to determine the temperature gradients, the rate of solidification and the local solidification times for the model of chemical and structural heterogeneity.
The points in the block and the chill were selected for comparison (**Fig. 8**). The computation and experimental curves are in **Figs. 9 and 10**. It is obvious that in the compared points of the mould and chills the results from the numerical model correspond to those measured, which applies to most other places where both the mould and chills were measured. In the centres of the block it was not possible to carry out the comparison due to a failure in the thermocouple probes.

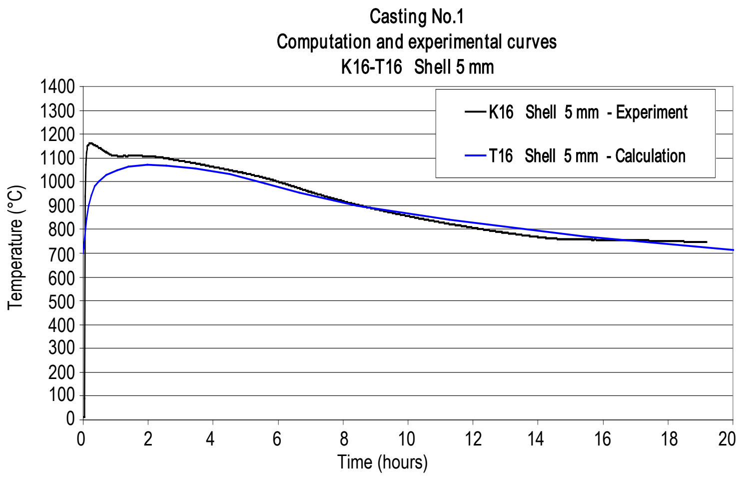

Fig. 9. The measured and calculated temperature history in the block 5 mm beneath its surface (chills on one side)

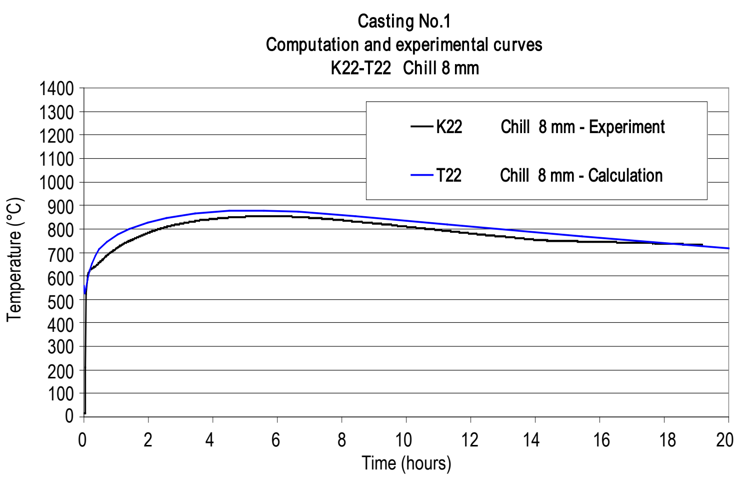

Fig. 10. The measured and calculated temperature history in the chill for the block (chills on one side)

The described connection of the temperature measurement with the 3D model of a non-stationary temperature field, which makes it possible to determine the local solidification time, seems to be the means via which it is possible to estimate the differences in structural characteristics of graphite in cast-iron and also the effect of the local solidification time on ductility in the casting.

2.3 A stone-block from ceramic material EUCOR

Products from EUCOR are used primarily in the construction of glass furnaces, in some steelmaking equipment, especially in heating furnaces, etc. They are highly resistant to molten glass and metal and are also suitable for cases of sudden temperature changes. Plates made of this material are therefore very suitable for walls and bottoms of melting aggregates, linings, casting filters, insulation plates and for a number of other purposes that may be accessible after optimizing their production technologies and utility properties [11]. From a foundry point of view, it is possible to compare the properties of EUCOR with those of common cast materials, in particular steel and cast iron [12].
The assignment focused on investigating the transient 3D temperature field of a system comprising a casting with a riser, the mould and ambient, using a numerical model. The dimensions of the system casting (the so-called stone)-riser-mould are given in **Fig. 11**. The initial temperature of the mould was 20 °C. The pouring temperature of the melt was 1 800 °C. That was approximately 300 °C higher, when compared with, for example, the steel pouring temperature. The temperature of the liquidus was 1 775 °C and the solidus 1 765 °C. The temperature field was symmetrical along the axes, i.e. it was sufficient for the investigation of the temperature field of a single quadrant only (**Fig. 14**).
The investigation of the temperature field of the pouring of a stone-block from ceramic material EUCOR had two goals: The directed solidification as the primary condition for a healthy casting and the optimization of the casting technology, together with the preservation of optimal utility properties of the product. The numerical model for the simulation was created by ANSYS again [13].

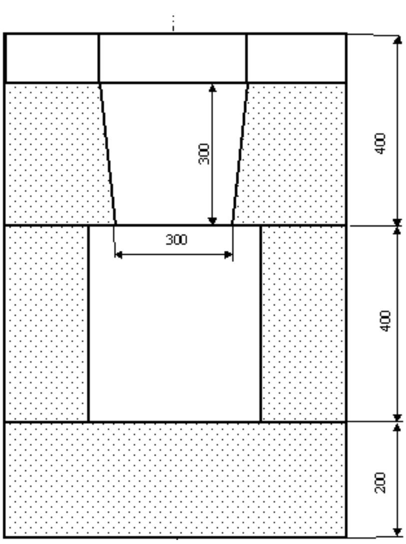

Fig. 11. The casting-riser-mould system

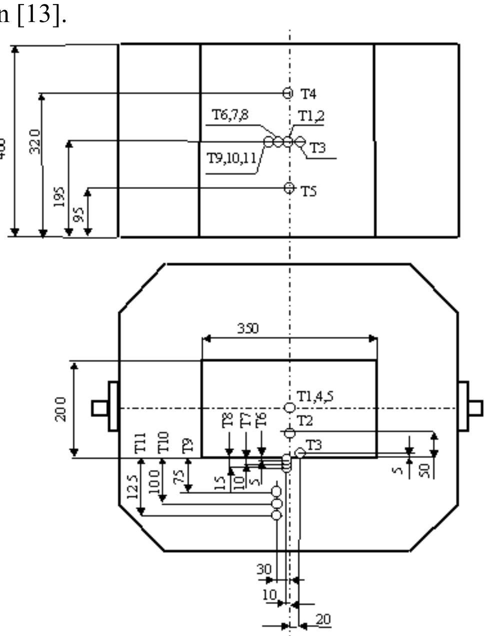

Fig. 12. Measurement points

The model was confronted with experimental measurements in the points T1-T11 and corrected (**Fig. 12 and 13**). The temperatures were measured in the actual casting and also in the mold [14]. Special tungsten-rhenium thermocouples had to be used for the measurement within the actual casting, in order to withstand the high pouring temperature. The temperature measurement lasted as long as 19 hours. The model of chemical heterogeneity was linked again to the results of the temperature model.

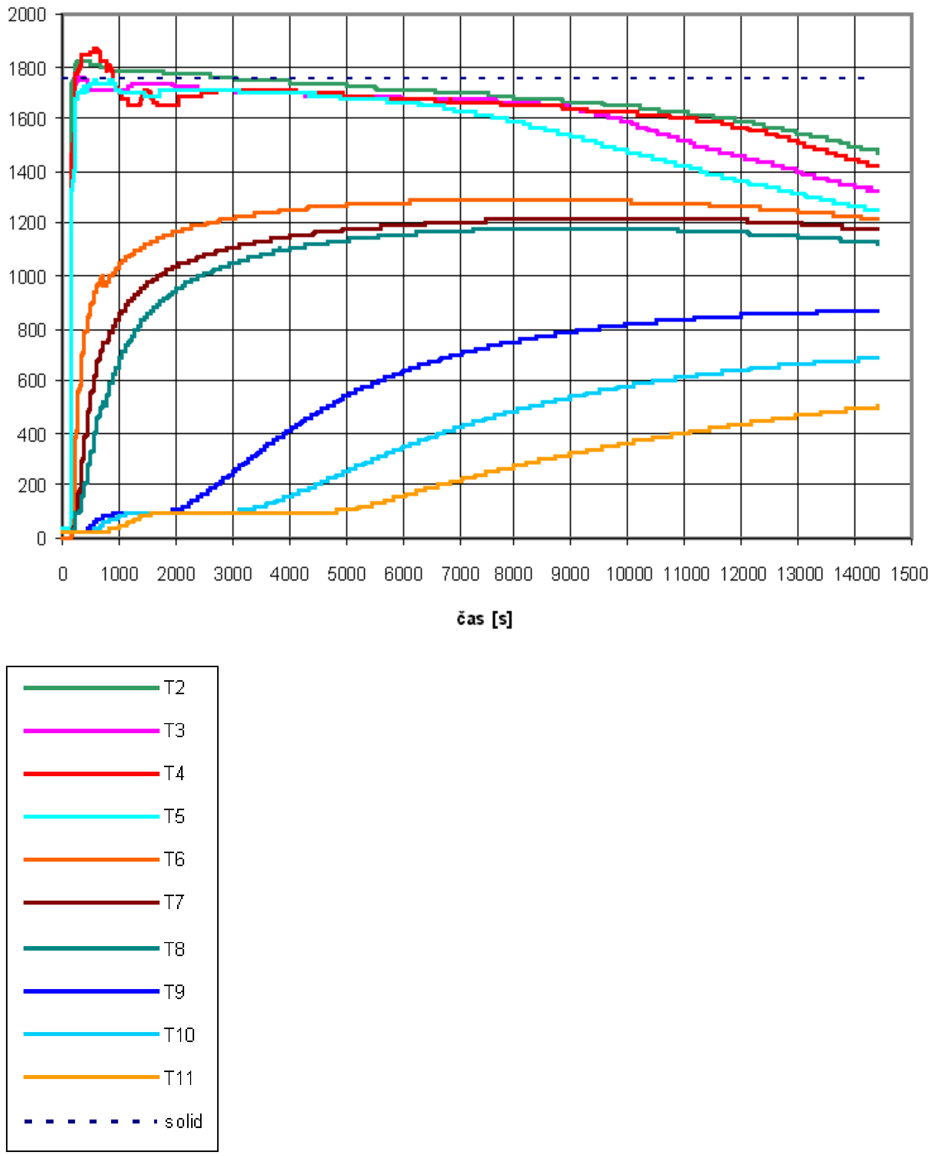

Fig. 13. The measurement points and the measured and computed temperature history of the points T5 and T6

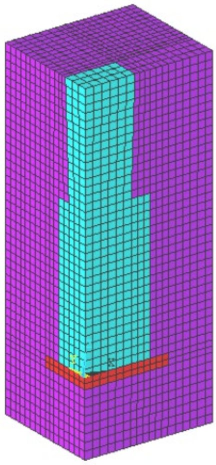

Fig. 14a. The 3D mesh of the system with the original riser

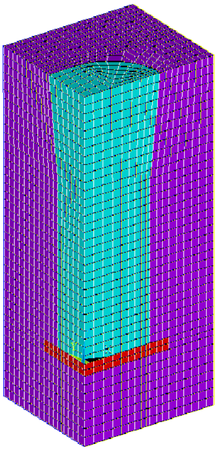

Fig. 14b. The 3D mesh of the system with the optimized riser

In both graphs on **Fig. 13** the blue lines represent the measured and the red lines represent the computed values. The comparison has been satisfactory, however, using the original riser, the directed solidification (which was the primary condition for a "healthy" casting) was not achieved because the riser was 'frozen' (i.e. the 'refilling' of the casting from the riser was cut off) at 5 200 s after pouring. Therefore the new shape of the riser was selected according to the latest findings. After several modifications, the application with an optimized riser ensured the directed solidification (**Fig 14b**).

2.4 The concast steel slab 1530 × 250 mm

The successful application of a numerical model (for example of a steel slab) and its continuous improvement is necessarily conditioned by carrying out demanding experiments and their evaluation [15, 16]. The measured parameters serve either as direct input data for the numerical model or they are used for the creation of this input data. This is, for example, the case of determining the heat transfer coefficients beneath the cooling jets that has to be carried out in the laboratory (see below). The range of the measurements carried out and applied was relatively considerable. They can therefore be divided into experimental research carried out on an operational device (caster) and experimental research carried out in laboratory conditions [17]. Research conducted on the operational device comprises permanent monitoring of the necessary physical and technological quantities during the entire process. Some of them are part of a so-called breakout system. This entails relatively extensive files of values containing individual data as well as time records – for example temperature in the walls of the mould, surface temperatures of the slab in the place of the bend, the pouring temperature, the casting speed, the temperature of the cooling water, etc. Furthermore, other experiments were also conducted for the purposes of research. This includes, for example, measurement of the surface temperatures in other places of the secondary-cooling zone (i.e. the cage), after exiting the cage (in the so-called tertiary-cooling zone) [18] and more. Experimental work in the operation is very expensive and complicated even from the organisational standpoint because this must not influence in any way the actual production. It is therefore necessary, for the setting up of the model, to utilise the quantities that have been measured within the existing caster control system. Due to the volume of data and the variety of the experimental work and its results, the procedure will be discussed only briefly, together with an example of the values measured. The most common measured quantities are the temperature of the steel, the flow of water through the mould and its heating up, the temperatures of the plates of the mould and the surface temperatures in the unbending point.

2.4.1 Measuring temperatures in the mould (crystallizer) and in the secondary cooling zone

Fig. 15 illustrates the positions of 44 thermo-couples in two lines along all walls of the mould.

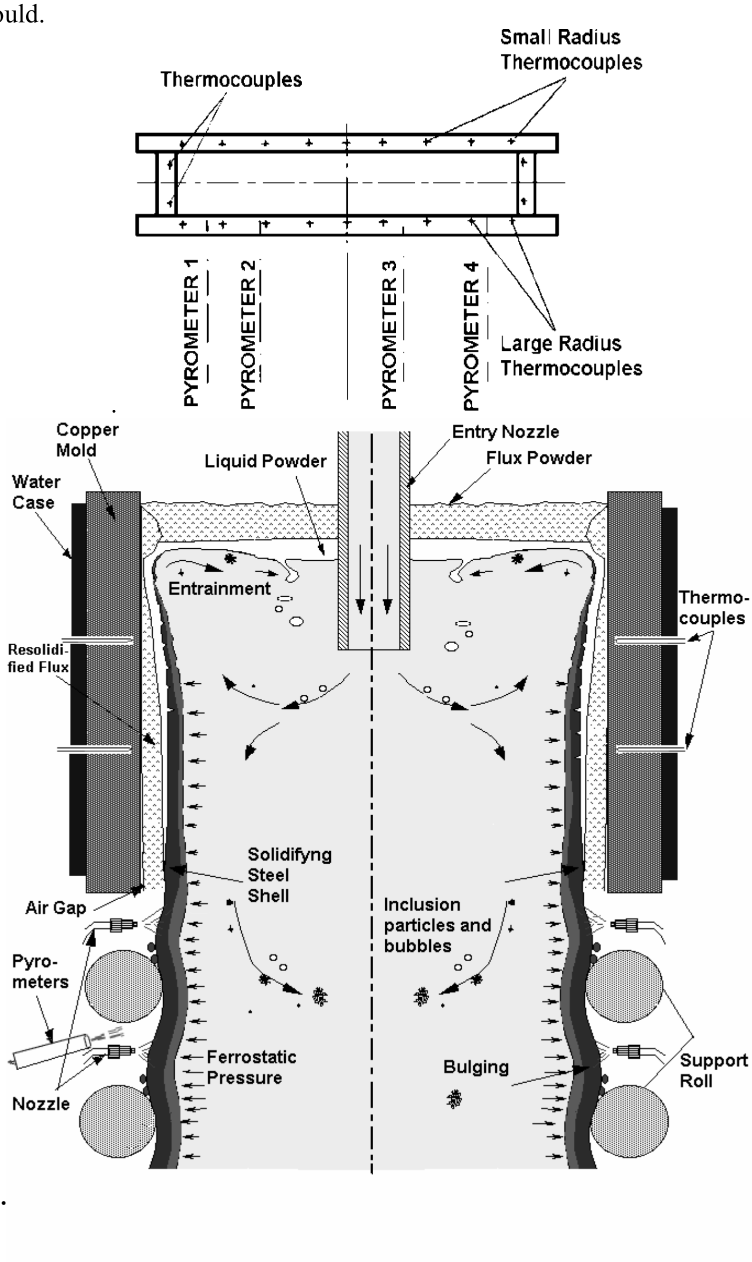

Fig. 15.

Fig. 16 presents the calculated temperature field of the slab 1 530 × 250 mm for this class of steel. The calculation of the temperature field of the same slab was performed also for other steels. In order to analyse the influence of the chemical composition on the temperature field more clearly, the other concasting parameters were used identical, i.e. the casting speed 0.8 m·min^{-1}, the superheating temperature 30 °C and the profile of the slab, just like the flow of water through the secondary-cooling zone. In practice, a different cooling mode is selected for each different class of steel.

.

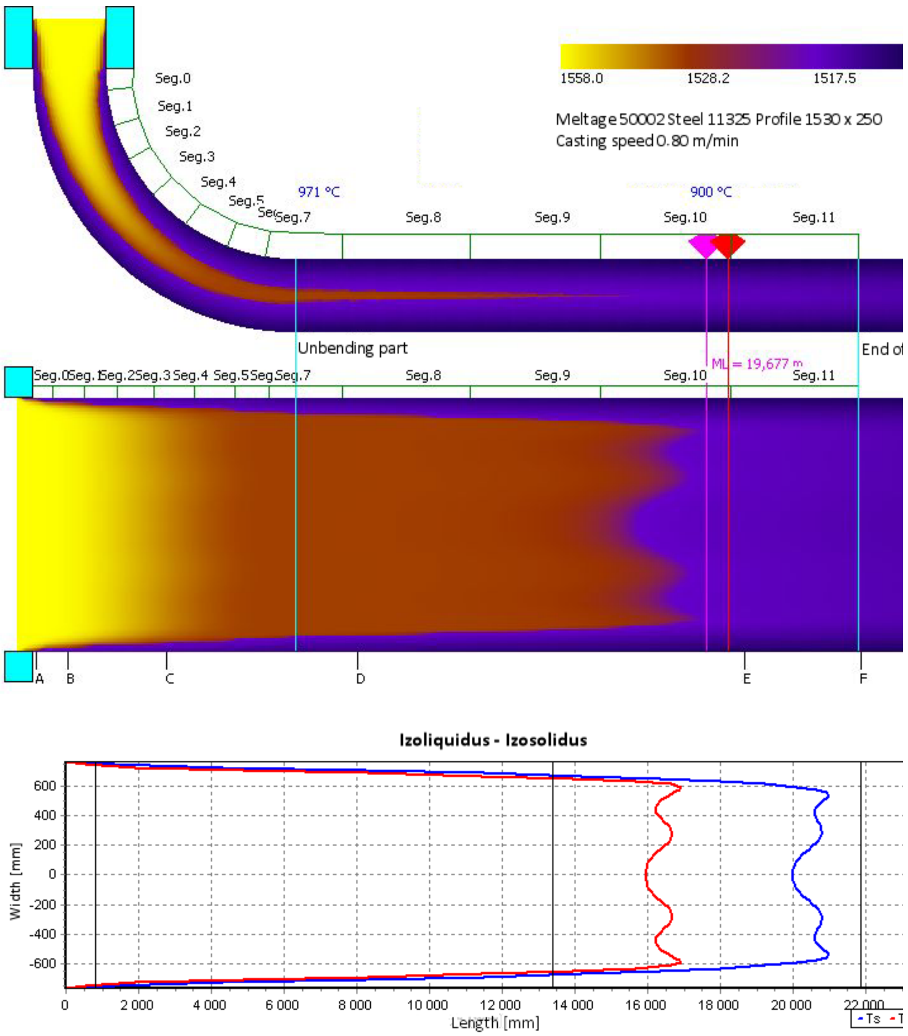

Fig. 16. Temperature field of the 11325 class steel slab

In order to make the model of the temperature field of the mould more accurate and to verify it, it is useful to carry out experimental measurement of the surface temperatures immediately below the mould, i.e. in the area of the retaining rollers. The measurement is carried out using optical pyrometers positioned at the centre of the slab, half-way between the centre and the edge and near the corner (**Fig. 15**). This measurement also makes it possible to assess whether the temperature field is

symmetrical along the axis of the cross-section. **Fig. 17** shows the measurement of the surface temperatures along the large radius in the area of the retaining rollers. The graph illustrates that it is necessary to process the data before it is used, i.e. it is necessary to find a suitable method of filtering. The generally used method of filtering is floating averaging. Its disadvantage is that large deviations are spread along a larger area. The median recursive filter brings the strongest filtration – its output is, for example, usable for the regulation of the secondary cooling. It is possible to consider that interference of the signal from the pyrometer is caused by a quality surface of the slab (scales and solidified casting powder). That is why the maximal values provided by the maximum filter are considered as correct.
The course of the temperatures measured immediately below the mould is not symmetrical along the longitudinal axis of the wider wall of the slab. This also means that even the heat released through the walls of the mould is not symmetrical. This is confirmed by the courses of the temperatures recorded by the breakout system, which means that if it was desirable to use the calculated temperature field in the model of the structure formation, i.e. the heterogeneity or in the model of temperature stress and strain, it would be necessary to investigate the entire slab and not only one symmetrical half of the cross-section. The experimental temperatures could be used from the breakout system (and not the data from the pyrometers), which, with respect to the densely arranged thermocouples in two horizontal planes (**Fig. 15**) covers the asymmetry better. In order to apply the dynamic model of the temperature field, the investigation of only one half of the slab is sufficient. **Fig.17** illustrates the favourable comparison of temperatures measured by three pyrometers with a calculated curve of the surface temperatures of the slab after 4 000 s.

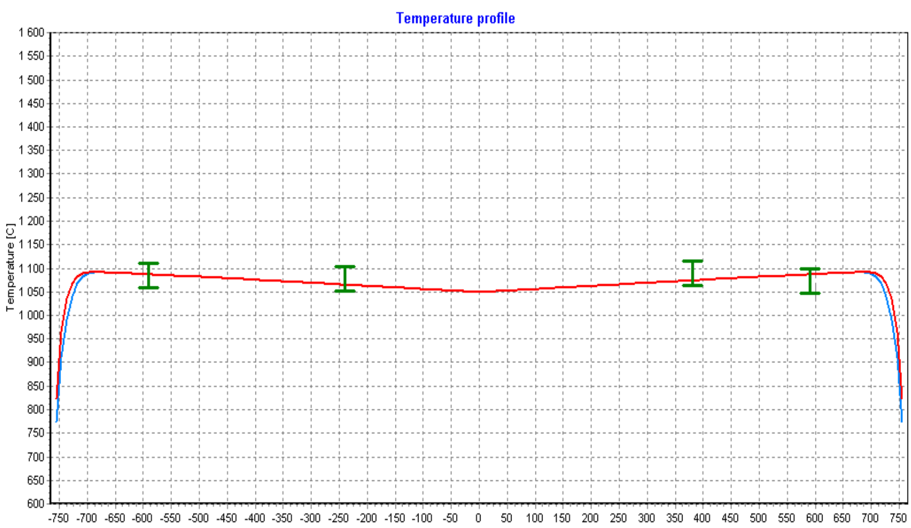

Fig. 17. A comparison of the course of the calculated and measured temperatures after 4000s

In order to make the model of the temperature field more accurate and to verify it, it was necessary to use two permanently installed pyrometers with both measuring the upper surface of the slab along the small radius. The first was installed by Mannesmann Demag already at the stage of starting up the caster. It is positioned just before the unbending point. This pyrometer was originally used for checking the function of the process secondary cooling. During the integration of the on-line model into the system, it is now used for comparing the temperatures calculated by the model with the real ones. Furthermore, it was joined by another pyrometer of the same type at the exit from the cage. This arrangement of both models also includes a processing unit that filters the measured data. This facilitates their utilisation because the software of the temperature model no longer has to deal with the filtering of the signal. The pyrometers measure within the range from 750 to 1 200 °C and in the case of a measurement failure it shows a temperature of 700 °C. The positioning of the pyrometers in the two mentioned points is necessary for the purposes of checking. The temperature of the slab in the point of the first pyrometer at the beginning of the unbending (point) must be higher than the temperature prescribed for this point (i.e. a slab that is too cold must not be straightened out). On the other hand, the temperature at the exit of the cage should be lower than the prescribed temperature.

2.4.2 Measuring of the metallurgical length

Determining the metallurgical length via the radioisotope method is more demanding (technically, economically, as well as administratively) than temperature measurement using thermocouples or pyrometers.
The determination of the farthest solidifying point – from the level – could be facilitated by contaminating the liquid metal using a radioactive indicator (e.g. a lead body inside a protective casing, enabling its melting at a safe distance from the mould) and its successive revealing using radiograms. This method, however, is not permitted by safety and legislative regulations. A solution is the combination of two indicators:

- A point gamma-radiation source in the geometric centre of a lead body that will not melt and which will be cut out and stored safely in the radioisotope laboratory after the slab is measured.
- Inactive lead bodies for determining how far into the solidification cone they penetrate, using chemical analysis.

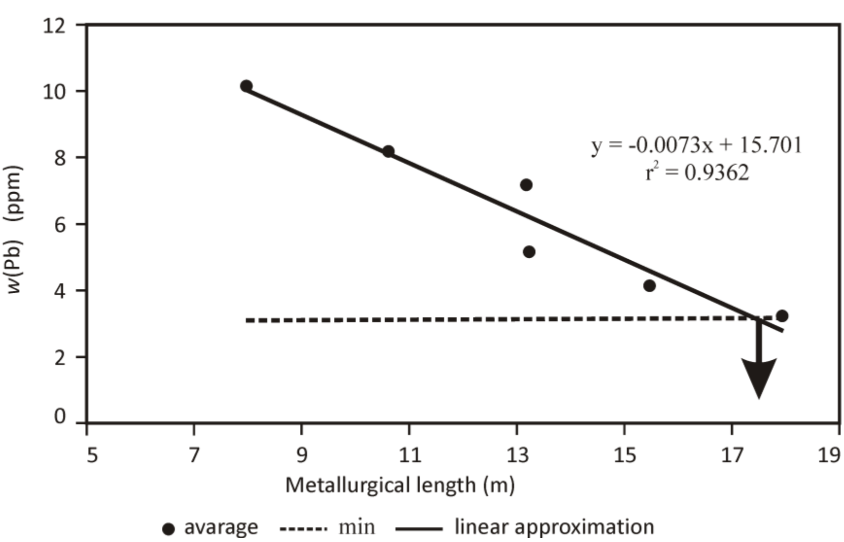

Fig. 18. Determining the metallurgical length (graphical extrapolation)

The point sources (low-carbon-content steel cylinders containing the radionuclid Fe 59, 20 MBq, 22 mm long, with diameters of 10 mm) were cast in inactive lead, in the centres of 120 mm cylindrical sheet-metal containers with external diameters of 100 mm.
A total of four attempts were made at measuring the metallurgical length. The first was a trial, in order to overcome problems concerning the detection of the passage of the emitters, i.e. the premature catching of the lead bodies on the dendrites of the shell of the solidifying slab, where the lead does not reach the apex of the solidification cone. The metallurgical length was determined as 17.4 m (**Fig. 18**) using mathematical and graphical extrapolation [19]. The calculation revealed that there are really two solidification cones. Experimentation confirmed this fact (see **Fig. 16**).

3. Conclusions

The investigation of the temperature field had two goals: The directed solidification as the primary condition for a healthy casting and the optimization of the casting technology, together with the preservation of optimal utility properties of the product. The achievement of these two goals depended on the ability to analyze and, successively, to control the effect of the main factors which characterize the solidification process or accompany it. Optimization of these processes is unthinkable without numerical simulation of the non-stationary temperature field during solidification including phase change and cooling. However, it is also necessary to refine and correct the results of the numerical model by experimental measurements. The importance and benefit of experiments is shown as an example in the numerical optimization of gravity casting of massive castings from steel and ductile cast-iron or material EUCOR as well as in the numerical optimization of continuous casting of a steel slab.

References

1. J. Miettinen, S. Louhenkilpi and J. Laine, Solidification analysis package IDS. In Proceeding of General COST 512 Workshop on Modelling in Materials Science and Processing, M.Rappaz and M. Kedro eds., ECSC-EC-EAEC, Brussels (1996)
2. F. Kavicka, J. Dobrovska, J. Stetina, J. Katolicky, J. Heger, Numerical Models of Solidification and their Application in Metal and Ceramic Technology. Litera Brno (2016)
3. J. Heger, Solution of the inverse heat transfer problem in the mold wall at concasting. In Proceedings and CD ROM of the National conference with international participation ENGINEERING MECHANICS, Svratka, Czech Republic, 30-34, May (2001)
4. J. Stetina, F. Kavicka, J. Katolicky, T. Mauder, L. Klimeš, Začlenění dynamického modelu BrDSM teplotního pole plynule odlévané bramy do řídicího systému ve VÍTKOVICE STEEL. Hutnické listy, LXX, 1, 15-20 (2017)
5. J. Heger, et al., Numerical optimization of the method of cooling of a massive casting of ductile cast-iron. Materiali in tehnologie/Materials and technology, 43, **2**, 73–78 (2009)
6. J. Molínek, et al., Optimization of technological parameters of the gravity-cast rolls for rolling. Final research report of the project GAČR GA106/04/1334, Ostrava, Czech Republic (2007)
7. J. Dobrovska, et al., Temperature Field and Solidification Structure of a Ductile-Cast-Iron Roller. Key Engineering Materials, 592, 1, 197–200 (2014)

8. J. Dobrovska, et al., The Character of the Solidification Structure of Massive Ductile Cast-Iron Castings and its Prediction. In Proceeding of 23rd International Symposium on Transport Phenomena (ISTP 23), Auckland, New Zealand, 50-55 (2012)
9. J. Heger, et al., Numerical optimization of the method of cooling of a massive casting of ductile cast-iron. In Proceedings of 22nd Canadian Congress of Applied Mechanics, Dalhousie University Halifax, Nova Scotia, Canada, p. 21-24, May (2009)
10. K. Stransky, et al., The character of the solidification structure of massive ductile cast-iron Casting and its prediction. Materials Science Forum, 567-568, 109–112 (2007), ©2008 Trans Tech Publications, Switzerland.
11. F. Kavicka, et al., Castings from corundo-baddeleyit ceramics – their properties and utilization for wear resistant materials, piping, etc. Slévárenství, 49, 9, 524–529 (2001)
12. F. Kavicka, J. Stetina, J. Katolicky, T. Mauder, L. Klimes, A simulation similarity of the process of solidification of steel castings and castings from EUCOR. In Proceedings of 54th Foundry days, Czech foundry company, Brno, September, 15-25 (2017)
13. J. Heger, et al., The experimental and numerical investigation of the solidification of a porous ceramic casting. Frontiers in Heat and Mass Transfer (FHMT), 3, 3, 1–9 (2012).
14. J. Molínek, et al., Problems of temperature measurement at corundum-baddeleyit ceramics casting. Acta Metallurgica Slovaca, 5, 2/3 (2001)
15. J. K. Brimacombe, The Challenge of Quality in Continuous Casting Process. Metallurgical and Materials Trans. B, 30B (1999), 553–566
16. B. G. Thomas, R. J. O'Malley, D.T. Stone, Measurement of temperature, solidification, and microstructure in a continuous cast thin slab. Paper presented at Modeling of Casting, Welding and Advanced Solidification Processes VIII, San Diego, CA, TMS. 1998.
17. J. Stetina J., et al., The numerical and Experimental investigation of a concasting process, The Book of Abstracts of the ASME/JSME Thermal Engineering Joint Conference, Kohala Coast, Hawaii USA, March 2003, p. 103.
18. R. A. Richard, R. Harding, Kai Liu, Ch. Beckermann, A transient simulation and dynamic spray cooling control model for continuous steel casting, Metallurgical and Materials Ttransactions, 34B (2003), 297–306.
19. J. Stetina, F. Kavicka, J. Dobrovska, Mathematical model for the calculation of the temperature field of a billet in real time. In Book of Abstracts and CD ROM of the 13th International Heat Transfer Conference, Sydney, Australia, August 13-18, 2006, p. 26.