A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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IDENTIFICATION OF THE BOUNDARY CONDITIONS IN THE CONTINUOUS CASTING OF STEEL

IDENTYFIKACJA WARUNKÓW BRZEGOWYCH W PROCESIE COS

The results of investigations relating the determination of thermal boundary conditions for continuous casting of steel were presented in the paper. The slab of dimensions 1100 mm x 220 mm was analyzed. In numerical calculations two models were compared. The first was the simple one and it used average heat transfer coefficient in both cooling zones. The second one used complex models in primary and secondary cooling zones. The presented models were verified on basing on an industrial data base. The problem was solved by the finite element method and the commercial numerical packet ProCAST.
Keywords: continuous, casting of steel, boundary conditions, numerical modeling

W pracy przedstawiono wyniki badań dotyczących wyznaczenia termicznych warunków brzegowych dla procesu ciągłego odlewania stali. Analizie poddano wlewek płaski o wymiarach 1100 mm × 220 mm. W obliczeniach porównano modele uproszczone, wykorzystujące średni współczynnik wymiany ciepła w strefie chłodzenia pierwotnego i wtórnego oraz modele rozbudowane. Zaprezentowane modele zweryfikowano na podstawie przemysłowej bazy danych. Zadanie zostało rozwiązane metodą elementów skończonych z zastosowaniem pakietu numerycznego ProCAST.

1. Preface

Slab solidification is a complex process. Heat is transferred from liquid steel through a solid layer and a air gap to a mold, intensively cooled with water. Hot liquid metal pouring through submerged entry nozzle to a mold causes liquid steel movement. Heat transfer between a strand and a mold is complicated and hard to define. All three heat transfer mechanisms appear here, namely convection, radiation and conduction. In the secondary cooling zone cooling of a strand occurs in the form of heat transfer with cooling water and mainly because of radiation of hot strand's surface[1]. An outer side of a mold is intensively cooled with water flowing through its channels. Here, forced convection is the dominant heat transfer mechanism. The solidifying strand's temperature field is described by the thermal conduction equation with the convection part (the Fourier – Kirchhoff equation). The solution of the equation is a temperature field T that should meet boundary conditions on a strand's surface.

The problem of the field temperature modelling in strands' solidification is raised by many authors. Commercial programms are in use as well as one's own [1]-[10]. Description of boundary conditions found in the literature is often limited to mean value in the mold's zone, thus greatly simplifying a heat transfer model.

The goal of the paper is identification of boundary conditions basing on the industrial data and to show the way their simplification influences solidifying strand's temperature field. In the presented calculations the heat transfer model given in the literature [8] was adopted and used along with the ProCAST commercial package. The packet uses the enthalpic method to solve the given problem. The method itself is described accordingly to the equation [11]:

$$H(T) = \int_0^T c_p(T)\,dt + L(1 - f_s) \qquad (1)$$

where:

H – enthalpy kJ/kg

c_p – specific heat kJ/(kgK)

L – latent heat kJ/kg

f_s – solid phase fraction

The enthalpy value has been set as a function of temperature, considering latent heat of solidification. The

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values have been determined in the experimental way for the tested steel sample. The solid phase fraction has been determined in the ProCAST application also as a temperature function within solidus-liquidus range.

The received results were verified on the basis of the industrial measurement done on a CCS line.

2. The results of the measurement done on the CCS machine

The device being analyzed is prepared to cast slabs. While measuring, following parameters were taken on the CCS machine:

1. The temperature of water cooling each of the mold's walls
2. The increase of the water's temperature on each of the mold's walls
3. The flux of water flowing through each of the mold's walls
4. The flux of water flowing through the nozzles within the secondary cooling zones
5. The temperature of the strand

The parameters 1 – 4 have been selected basing on the measurement done by devices installed on the CCS machine. The results of the measurement are shown in the Tables 1 and 2. The values given in each table are the mean values derived from all the cycle of measures.

TABLE 1

The results of the measurement on the CCS – mold line

	Water stream, dm^3/min	Temperature increase, °C
Broad faces 1	2951.556	3.66
Broad faces 2	2984.007	3.81
Narrow faces left	393.5014	4.53
Narrow faces right	396.8747	4.56

TABLE 2

The results of the measurement on the CCS – spray cooling line

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Location of zones, mm	900 – 1095	1095 – 3060	3060 – 6715	6715 – 10915	10915 – 15090	15090 – 18270
Water stream, $dm^3/(m^2s)$	5.0	2.60	1.26	0.71	0.35	0,12

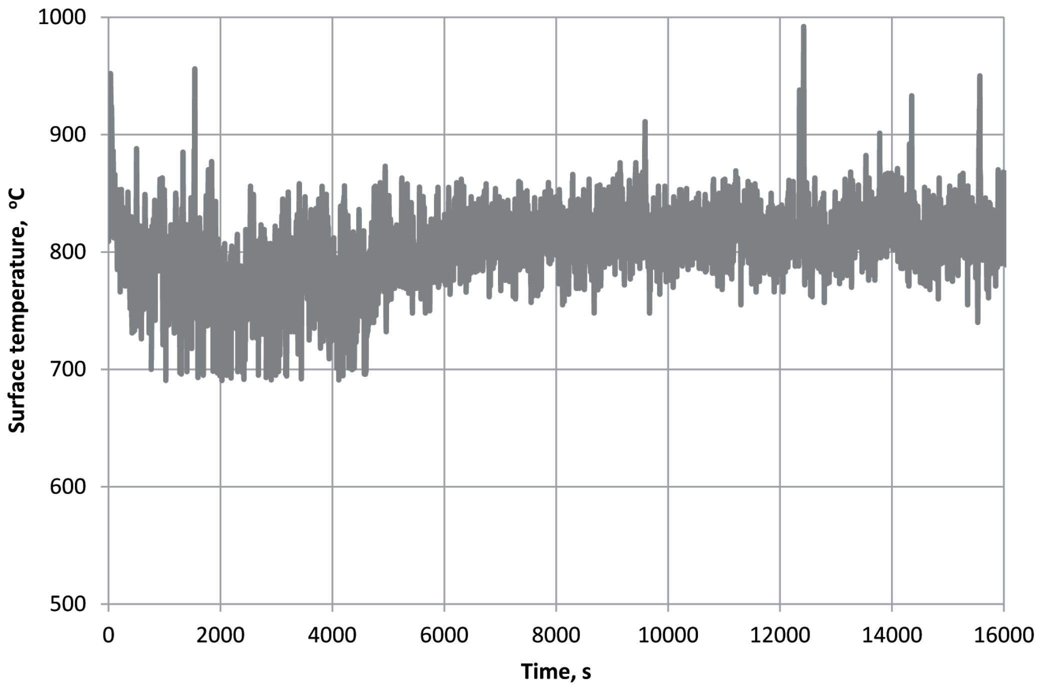

Fig. 1. The change of the strand's temperature during the tests

TABLE 3

Chemical composition of steel

C	Mn	Si	P	S	Cr	Ni	Cu	Al	V	Mo
0.07	0.6	0.03	0.02	0.018	0.15	0.15	0.15	0.045	0.02	0.05

The surface's temperature have been captured by the pyrometer additionally installed for the time of measurement. The place to measure have been selected as close to the mold as possible, i.e. around 2.2 m below its lower edge. The chart (Fig. 1) shows the way the surface temperature changed during the CCS process.

The S235C steel sequence was casted on the CCS machine while measuring. Its chemical composition is shown in the Table 3.

For given steel composition, the values of thermodynamic properties for the modelled steel were calculated using the ProCAST packet. The values of the heat transfer coefficient, the density and the fraction of solid phase in the function of temperature are shown at Fig. 2.

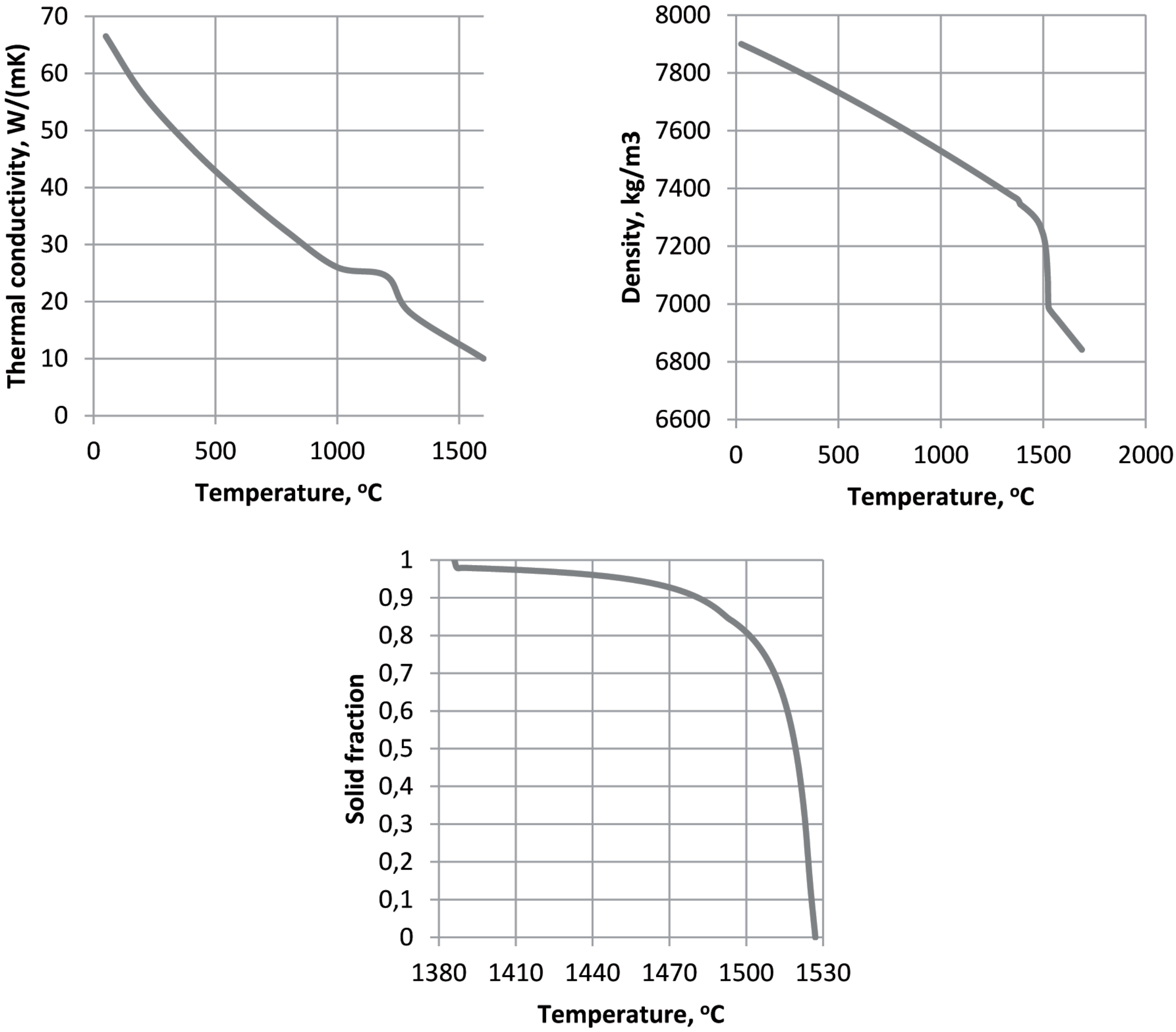

Fig. 2. The heat transfer coefficient, the density and the fraction of solid phase in the function of temperature

The enthalpy value were determined experimentally and put into the ProCAST application according to the equation (1).

3. The boundary conditions model

In order to identify boundary conditions better, border surfaces have been splitted into:

1. Primary cooling zone – inner side of mold – soldifying strand's surface
2. Secondary cooling zone
3. Liquid steel surface
4. Outer side of mold cooled with water

For points 1, 2 and 4 the boundary condition has been given as the heat transfer coefficient value. For the 3^{rd} point the Dirichlet boundary condition (temperature value) has been used.

Boundary conditions can be set in three different ways in the ProCAST software. It's described by the equation [11]:

$$Q = Flux + h(T - T_a) + \sigma\varepsilon(T^4 - T_a^4) \qquad (2)$$

The heat flux could be entered as the flux value or as the replacement heat transfer coefficient defined in the program as [h] or by setting the emissivity value [ε] in the case when heat is transferred by radiation. The application allows to carry out computations using each and every of forementioned ways, however, a simulation may be run with only one parameter selected by the user.

Concerning the heat transfer model in the primary cooling zone described in the literature [8], a mold has been split into two regions. In the first one, heat was transferred by convection. Liquid steel is in contact with the mold. Below the solidus temperature, air gap occurs. In the heat transfer model applied for air gap, the two basic heat transfer mechanisms have been used: radiation and convection. The radiation heat transfer parameter h_r has been derived from the law of radiation between two flat surfaces slab – mold [8]:

$$h_r = \varepsilon_z C_o \frac{T_p^4 - T_k^4}{T_p - T_k} \qquad (3)$$

where:

ε_z – replacement emissivity coefficient

T_p – slab's surface temperature, K

T_k – mold's inner surface temperature, K

Heat transfer by radiation has been supplemented with the part defining the convectional heat transfer h_p derived from the empirical equation [8]:

$$h_p = (h_k - h_r)\, exp^{\frac{T_p - T_{SO}}{200}} \qquad (4)$$

where:

h_p – replacement coefficient of convectional heat transfer, W/(m^{2}K);

h_k – convectional heat transfer coefficient, W/(m^{2}K);

T_{SO} – solidus temperature, K

After leaving a mold, a strand's surface is cooled in spray cooling system and on the air. The heat flux from cooled strand is directly proportional to the difference between the strand's surface temperature and the temperature of a cooling medium.

Heat transfer coefficient depends on what conditions are applied during water – strand's surface contact. It's value is affected by water flux density, velocity of water pouring from spray nozzle, nozzle type, water pressure. Nozzle construction and the way of spraying water is also significant. It is correct to use the simplified equation when the strand's surface is unknown. The foresaid equation enables heat transfer coefficient and is of following form [12]:

$$h_{II} = 10v + (107 + 0.688v)\, w, [W/(m^2K)] \qquad (5)$$

where:

v – water drops' velocity, m/s

w– cooling water flux, dm^3/(m^{2}s)

Out of the water spray cooling zone the heat is transferred from hot strand's surface by the means of radiation and the natural convection or the forced one, when using blow ventilators. The heat transfer coefficient of radiation h_{r2} can be determined with the equation (3). Another heat transfer mechanism is convection. It can be described by the following equation for a laminar boundary layer that allows to determine the convectional heat transfer coefficient h_{k2} [13]:

$$Nu = 0.664 Re^{\frac{1}{2}} Pr^{\frac{1}{3}} \left(\frac{Pr}{Pr_p}\right)^{0.19} \qquad (6)$$

Overall heat transfer coefficient is equal to:

$$h_{III} = h_{r2} + h_{k2} \qquad (7)$$

An outer side of a mold is intensively cooled with water flowing through channels. In this case, heat is transferred by the forced convection. Because of the way heat is absorbed by water flowing through the channel it is hard to determine the heat transfer coefficient for the mold's channels following available equations [14]. To find the Nusselt number, the equation has been chosen [13]:

$$Nu = 0.021 Re^{0.8} Pr_w^{0.43} \left(\frac{Pr_w}{Pr_k}\right)^{0.25} \qquad (8)$$

where:

index w – for the mean water temperature in a channel

index k – for the strand's surface temperature

In order to compute the mean heat transfer coefficient h_{IV}, the following equation was used for the outer side of the mold [14]:

$$h_{IV} = \frac{Nu\lambda_w}{d_w} x_w \quad (9)$$

where:

x_w – the fraction of a surface cooled with water
d_w – the cooling channel diameter

4. The calculation variants

The two variants of calculation have been used for the solidification process. The first one was simple, with mean heat transfer coefficient values within the borders of primary and secondary cooling zones, while the second one was set with a complex secondary cooling zone.

The criterion that allows to find out whether the assumed heat transfer coefficient within the mold – strand system is proper or not is the limit of this coefficient achieved from the energy balance in a primary cooling zone system basing on measurement results. The mean value for tested machine was 1040 W/(m^{2}K). As mentioned before, this is lower limit, derived from the thermal balance of water cooling the mold. The heat lost from the outer side of the mold to environment was not taken into account in the simple balance.

For the 1st variant the following values have been used:

– heat transfer coefficient h_k = 1300 W/(m^{2}K) [15-16]

– mean temperature of the mold's surface T_k = 200°C [14]

– solidus temperature for the tested steel T_{SO} =1386°C

– emissivity of the mold ε_k = 0.6

For the given values the value of heat transfer coefficient inside a mold was determined. The result was h_I = 1050 W/(m^{2}K). In the secondary cooling zone the mean heat transfer coefficient was assumed for the whole zone and it was equal to h_{II-III} = 300 W/(m^{2}K). For the outer side of the mold cooled with water the value of the heat transfer coefficient h_{IV} was determined basing on the equation (9) and assuming that the fraction of channels' surface is x_w = 0.5. The boundary condition equal to the inlet temperature, namely 1550°C, has been set for the liquid steel surface. The changes of the heat transfer coefficient along the strand are shown in the Fig. 3. The simulation results acquired by using this variant have contributed to verify the property of assumptions made.

New values for boundary conditions have been derived from the analysis of results and following correction of the assumptions. In the 2nd variant the revised value of the heat transfer coefficient in a mold has been used, with its value equal to h_I = 940 W/(m^{2}K). It has been determined basing on the results of computations in the variant 1. In the secondary cooling zone the heat transfer coefficient changing for each cooling area has been set, according to the following:

- Area 1 – 900 mm – 1095 mm – h_{II} = 600 W/(m^{2}K)
- Area 2 – 1095 mm – 3060 mm – h_{II} = 500 W/(m^{2}K)
- Area 3 – 3060 mm – 6715 mm – h_{II} = 350 W/(m^{2}K)
- Area 4 – 6715 mm – 10915 mm – h_{II} = 280 W/(m^{2}K)
- Area 5 – 10915 mm – 15090 mm – h_{II} = 250 W/(m^{2}K)
- Area 6 – 15090 mm – 18270 mm – h_{II} = 220 W/(m^{2}K)
- Area 7 – 18270 mm – 23300 mm. Air cooling h_{III} = 86 W/(m^{2}K)

It enabled the modelling of a real system of spray areas with different intensity of water flux cooling the strand. Other parameters haven't changed. The changes of the heat transfer coefficient along the strand are shown in the Figure 3.

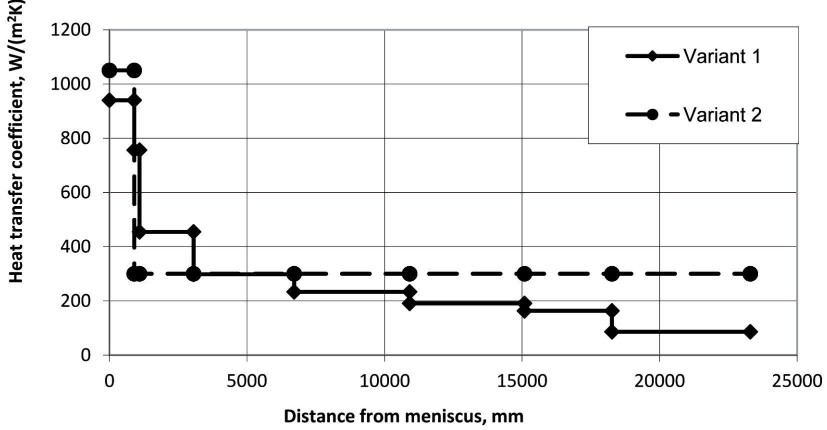

Fig. 3. The heat transfer coefficient used for the calculations

5. The calculations' results

The strand size of 1100mm×220mm has been used for the calculations. The casting velocity was equal to 0.78 m/min. The copper mold was 900 mm long. The heat transfer coefficient was equal to λ = 370 W/(mK), density ρ = 8900 kg/m^3, heat capacity c_p = 400 J/(kgK). The liquid steel inlet temperature was 1550°C. The mass movement has been implemented by setting the velocity zone equal to the mean casting velocity for all the area of simulation. The FEM method within the ProCAST software have been used.

The validation of the simulation results was done basing on measurement of the strand's surface temperature. The measured point was located 2.9 m from the meniscus of liquid steel and the mean temperature value was 810°C. The metallurgical length, which was approximately 10.5 m for the tested case, and the epidermis' thickness after leaving the mold were additional parameters of verification.

The temperature field for the 1st variant of calculations is shown in the Fig. 4. It allows to analyze the temperature field in the longitudinal section of the modelled strand. The course of the isotherms of the temperature field for the modelled case is correct. More in-depth validation is possible to carry out if based on the temperature distribution on the strand's surface (Fig. 5). The temperature value in the control point is too high and is equal to 1035°C. The metallurgical length for this variant is 13.4 m, while the data for the tested device states is should be 10.5 m. The changes of the temperature of the inner mold surface are shown in the Fig. 6. The highest surface temperature is found in the point of contact between the molten metal and the mold's wall and is around 240°C high. This variant of calculations has been used as a base for the following tests. The calculations for the 2nd variant have been done after revising the assumed temperature of the mold's wall and after applying areas of the secondary cooling zone with the heat transfer coefficients computed on the basis of the intensity of water spray.

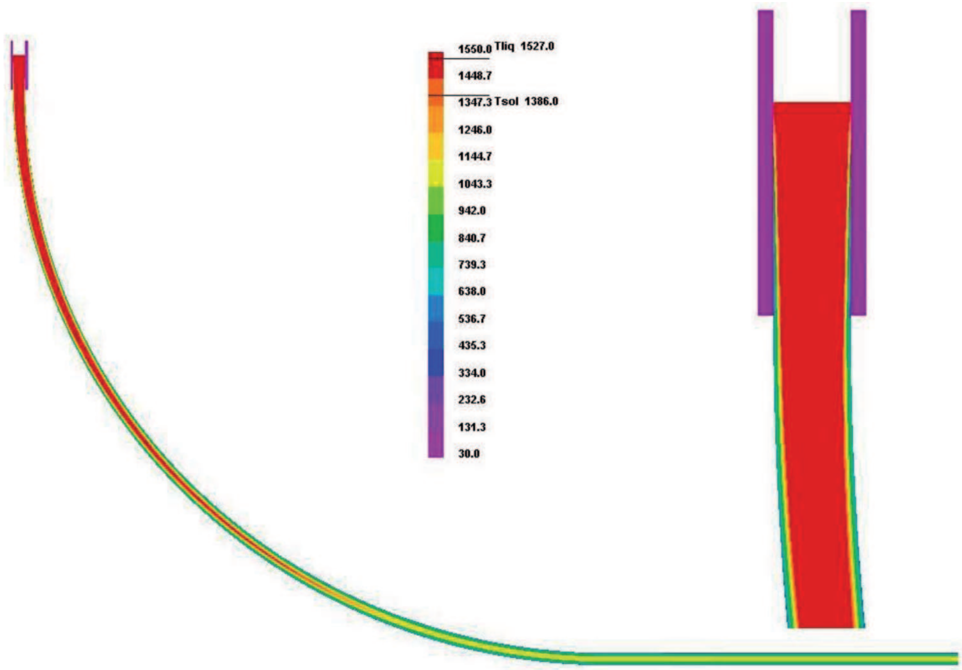

Fig. 4. The temperature field within the longitudinal section for the 1st variant

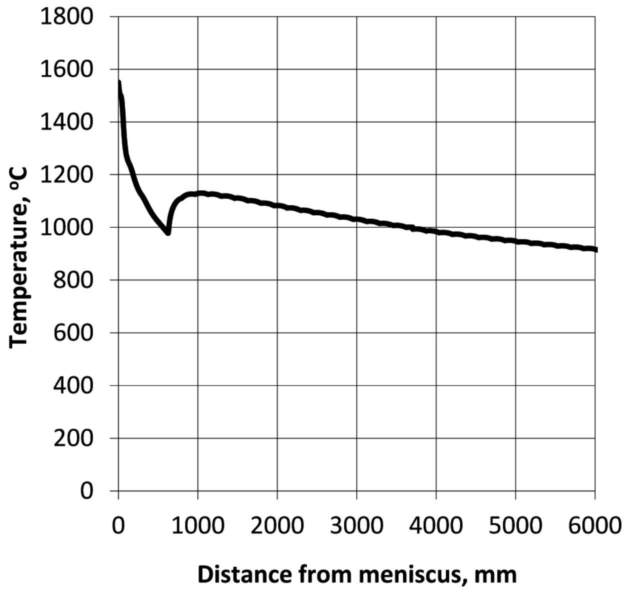

Fig. 5. The temperature distribution on the strand's surface for the 1st variant

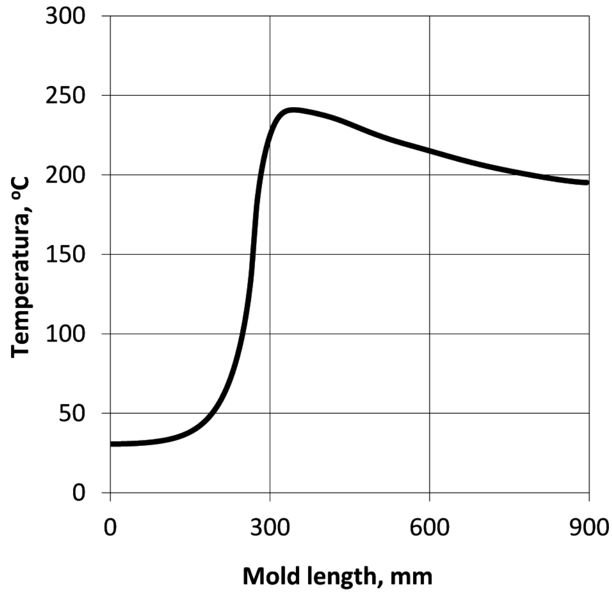

Fig. 6. The temperature distribution on the mold's surface for the 1st variant

The temperature field in the cross-section is shown in the Fig. 7. The course of the isotherms is correct for the modelled case. The differences between each variant's calculations can be seen in the temperature distribution of the surface (Fig. 8). It was possible to receive the correct temperature distribution of the strand's surface because the revised heat transfer coefficient within the mold and the areas of the secondary cooling zone were applied. According to the simulations, the temperature value in the control point is 800°C, while the mean value derived from the tests data is 810°C. The mold's surface temperature (Fig. 9) was brought down slightly. Its nature remained the same as in the 1st variant. The metallurgical length resulting from this variant is 10.4 m and is correct.

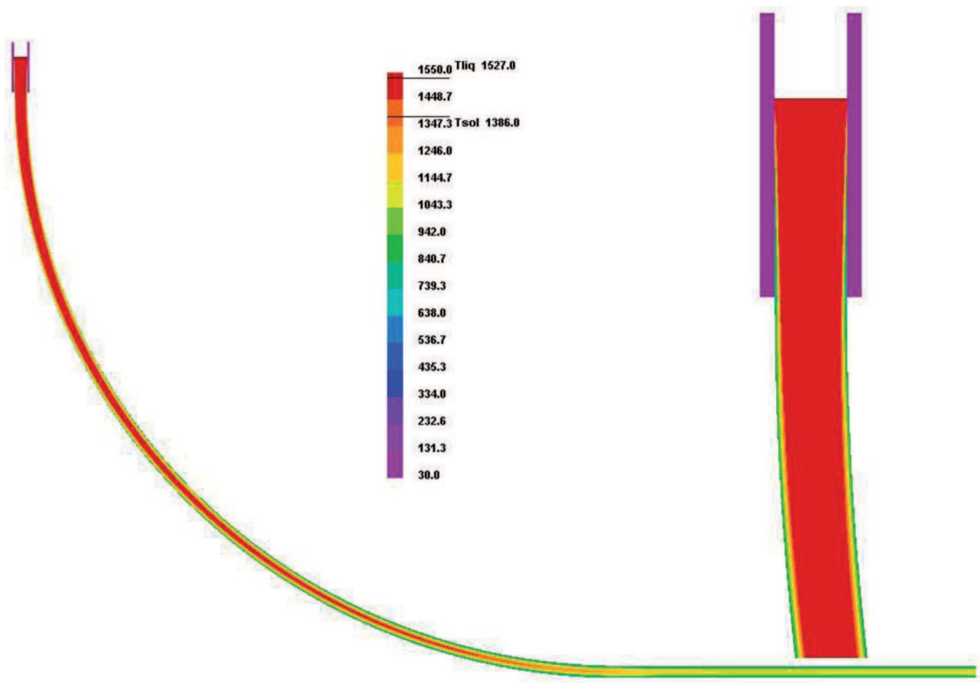

Fig. 7. The temperature field in the longitudinal section od the strand – 2nd variant

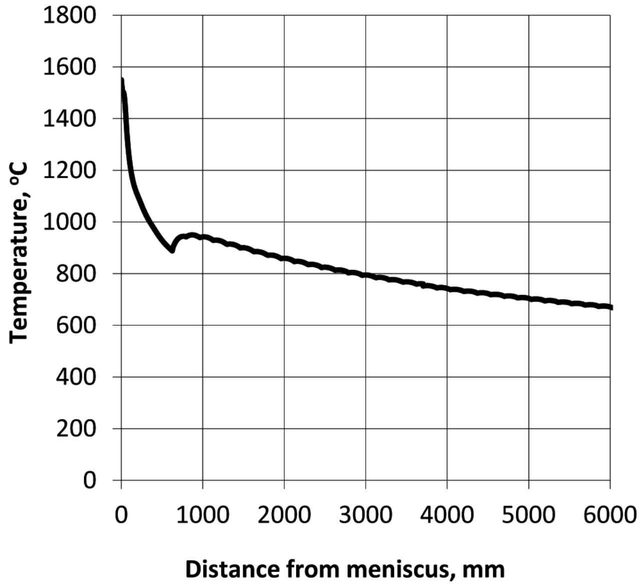

Fig. 8. The temperature distribution on the strand's surface for the 2nd variant

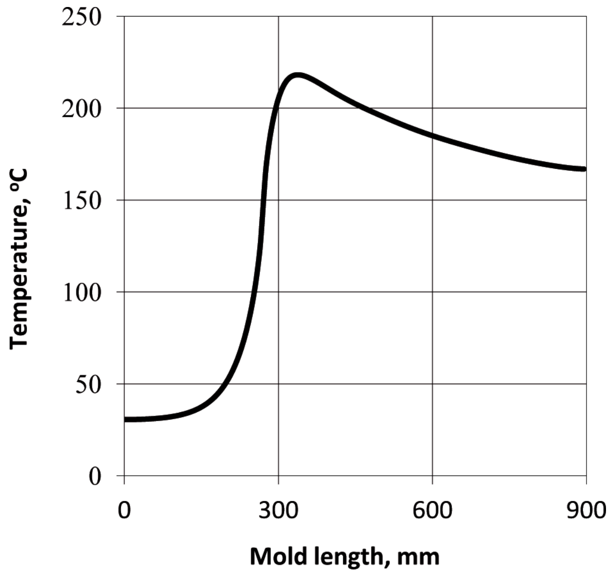

Fig. 9. The temperature distribution on the mold's surface for the 2nd variant

6. Summary

Within the article, the identification of the boundary conditions based on the industrial tests was shown. Additionally, the influence of simplifications on property of the solidyfying strand's temperature field was tested. Within the tests, the heat transfer model in a mold described in the literature have been implemented into the ProCAST packet.

Correct computation of the temperature field is a fundamental problem in the CCS process modelling. Any mistakes made in its determination cause incorrect results of simulations of other processes occurring in the continuous casting of steel.

The two ways of describing boundary conditions within the model used to simulate the strand solidification in the CCS machine have been analyzed. The first one have had a simplified cooling scheme with the mean heat transfer coefficients. Implementing those mean conditions into temperature field calculations does not show the true nature of the CCS strand solidification process. The surface temperature reaches too high values while the metallurgical length exceeds the one given for the tested machine. This variant of calculations can be used only for initial validation of numeric model assumptions made. The correct results were received after using the model with the secondary cooling zone split into several areas. Metallurgical length, ephidermis' thickness and surface temperature are the same as the experimental data. The differences between the two variants can be seen in the temperature field of both strand and mold. The development of the model hasn't caused numerical calculations to last longer. The wrong boundary conditions determination results in the incorrect values of solid layer thickness, temperature field and metallurgical length.

Using the heat transfer coefficient in a mold as a function of the mold's length will be the next step of the research – the complex model. It will allow to better show the real conditions of heat transfer within this part of CCS machine. The model build with the ProCAST software will be used to develop new cooling programms for the CCS process, what will result in increase of efficiency and decrease of energy absorption of the mentioned process.

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