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APPLYING A NUMERICAL MODEL OF THE CONTINUOUS STEEL CASTING PROCESS TO CONTROL THE LENGTH OF THE LIQUID CORE IN THE STRAND

ZASTOSOWANIE NUMERYCZNEGO MODELU PROCESU COS DO REGULACJI DŁUGOŚCI CIEKŁEGO RDZENIA W PAŚMIE

This paper presents development and the application of a numerical model of the continuous steel casting process to optimise the strand solidification area. The design of the numerical model of the steel continuous casting process was presented and which was developed based on the actual dimensions of the slab continuous casting machine in ArcelorMittal Poland Unit in Kraków. The S235 steel grade and the cast strand format of 220×1280 mm were selected for the tests. Three strand casting speeds were analysed: 0.6, 0.8 and 1 m min^{-1}. An algorithm was presented, allowing the calculation of the heat transfer coefficient values for the secondary cooling zone. In order to verify the results of numerical simulations, additional temperature measurements of the strand surface within the secondary cooling chamber were made. The *ProCAST* software was used to construct the numerical model of continuous casting of steel.

Keywords: continuous casting of steel, numerical modelling, optimization technological parameters, metallurgical length

W pracy przedstawiono zastosowanie numerycznego modelu procesu COS do optymalizacji obszaru krzepnięcia pasma. Zaprezentowano budowę numerycznego modelu procesu ciągłego odlewania stali, który opracowany został na podstawie rzeczywistych wymiarów maszyny do odlewania wlewków płaskich w Arcelor Mittal Poland Oddział Kraków. Do badań wybrano gatunek stali S235 przy odlewanym formacie wlewków 220×1280 mm. Analizowano trzy prędkości odlewania wlewka: 0.6, 0.8 oraz 1 m min^{-1}. Zaprezentowano algorytm pozwalający obliczyć wartości współczynników wymiany ciepła dla strefy wtórnego chłodzenia wraz z możliwością wyznaczenia natężenia przepływu w poszczególnych strefach natrysku. W celu weryfikacji wyników symulacji numerycznych przeprowadzono dodatkowe pomiary temperatury powierzchni pasma w komorze wtórnego chłodzenia. Do budowy numerycznego modelu COS wykorzystano pakiet oprogramowania ProCAST.

1. Introduction

In recent years the possibility of numerical modelling of metallurgical processes has been growing in importance with relation to creating a new technology and modifying what already exists. The mathematical modelling of solidifying processes with numerical methods makes a full comprehensive reconstruction of the complex physical and chemical character of those processes. Currently advanced computer programs are used for numerical modelling of the continuous steel casting process, and both proprietary and commercial simulation programs are used for this purpose. The utilization of numerical calculations for the analysis and identification of the existing process-related problem assists in finding an appropriate solution. It results in an improvement of production and the quality of the product. [1-7] Based on the existing casting technology for the continuous caster selected for this study, a numerical model of the process was formulated that allows the calculation of the temperature distribution within the whole volume of the solidifying strand. As part of this industrial research information was collated on the most important technological parameters in the steel continuous casting process. Because of the need to verify the model calculations, additional temperature measurements of the strand surface were taken during the heats investigated: an optical pyrometer and a thermovision camera were used. Verification of the correctness of the model calculations involved analysing the thickness of the shell leaving the mould, the metallurgical length of the strand (the length measured from the steel meniscus level in the mould to the point of total solidification of the strand – the length of the liquid core) and comparing the temperature calculated on the strand surface with the value measured at measurement points. The high accuracy of the temperature distribution on the surface of the solidifying cast strand that was obtained was key to solving the problem. Calculations were performed for three strand casting speeds: 0.6, 0.8 and 1 m min^{-1}, along with an appropriate set of heat transfer coefficients which were calculated on the basis of industrial data. The results of numerical simulations clearly indicated that the metallurgical length was the parameter that was characterised by the biggest discrepancy of the calculated values at various casting speeds. From the perspective of the

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applicable technology, as well as of the very design of the slab continuous casting machine concerned, it is essential to maintain the metallurgical length at a constant level.

2. The construction of the numerical model of the steel continuous casting process

The mould model and the whole strand model were designed with the SolidWorks program. A mould with a height of 900 mm, and a wall thickness of 40 mm, was implemented. Filling the mould with liquid steel was assumed at a level of 850 mm. A strand with an arc radius of 10.5 m, and dimensions of 220×1100 mm, was designed. The 3D model, with total number of elements equal 929908 and total number of nodes equal 179311, was implemented. The tetrahedral elements were used, in order to calculate temperature field in the model. At the stage of strand shape designing, the technological division into spray zones that were included in the secondary cooling zone was taken into account. The following breakdown of the secondary cooling zone was implemented:

1. The first zone of spray onto the wide strand sides: 900-1095 mm
2. The second zone of spray onto the wide strand sides: 900-1900 mm
3. The third zone of spray onto the wide strand sides: 1095-2930 mm
4. The fourth zone of spray onto the wide strand sides: 2930-6617 mm
5. The fifth zone of spray onto the wide strand sides: 6617-10768 mm
6. The sixth zone of spray onto the wide strand sides: 10768-14926 mm
7. The seventh zone of spray onto the wide strand sides: 14926-18271 mm

The above dimensions of the spray zones were designed on the basis of the actual dimensions of the secondary cooling zone of the continuous caster. The *ProCast 2013* software package was used to perform numerical calculations. The movement of a continuum may be described from two different standpoints – either by the Lagrangian or the Eulerian methods. The Eulerian approximation is best suited for describing the temperature field and the flow of liquid metal. A non-deforming finite element mesh, along with the unchanged geometry of the steel continuous casting process, were applied here.

2.1. Material-related parameters

The following thermal properties of the S235 steel from the experimental data – specific heat, along with the heat of solidification and thermal conductivity – were used to formulate the numerical model as regards the continuous process of steel casting. The values of density and viscosity – along with the liquidus and solidus temperatures – were calculated on the basis of the chemical composition of the steel examined with CompuTherm LLC thermodynamic databases. Table 1 presents the chemical composition of the S235 steel analysed.

TABLE 1

Chemical composition of the S235 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 numerical model of the continuous steel casting process uses the enthalpy method for calculations of the temperature distribution. This method is described as in the equation: [8,9]

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

where H is enthalpy, kJ kg^{-1}; c_p is specific heat, kJkg^{-1} K^{-1}; L is latent heat, kJkg^{-1}; $f_s$is solid phase fraction, [0-1]. In the material parameters, the enthalpy value H – or the specific heat value c_p, along with the latent heat L – may be declared. The experimental values of specific heat, and heat of solidification were implemented in the formulated numerical model. **Figure 1** presents the values of specific heat as a function of temperature. The latent heat value for the S235 steel was measured at 113kJ kg^{-1} [10,11].

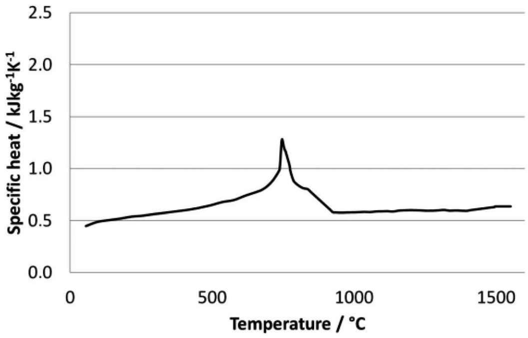

Fig. 1. Specific heat versus temperature for the S235 steel [10,11]

All phase transitions, accompanied by the latent heat, were implemented in the form of a numerical value. The magnetic transformation (a second-order phase transition) was taken into account as a change in the specific heat value. The liquidus temperature of 1527°C and the solidus temperature of 1493°C were calculated for the chemical composition of the steel presented in **Table 1**.

2.2. Boundary and initial conditions

Describing the heat transfer model in the continuous steel casting process is a complex task, as all three mechanisms of heat transfer occur within this process. The heat conduction occurs in the solid body zone, whereas in the liquid area we deal with both the heat conduction and the heat transport by the natural and forced convection. In the calculations presented, the heat transfer model was applied in which the temperature field could be determined by solving the Fourier equation:

$$\frac{\partial\left(\rho c_p T\right)}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + Q \tag{2}$$

where ρ is density, kg m^{-1}; c_p is specific heat, kJ kg^{-1} K^{-1}; λ is thermal conductivity, W m^{-1}K^{-1}; t is time, s; T is temperature, K; Q is heat source term, W m^{-3} ; x, y, z are 3D coordinate axes. The solution to the thermal problem is the T vector that represents temperature values in individual nodes of the finite element mesh. The solution of the Fourier equation should meet those boundary conditions declared on the strand surface. When solving the heat transfer problems in the formulated numerical model of the continuous steel casting process, two boundary conditions were defined in the main: the heat flux and the temperature on the selected model surfaces. In the formulated numerical model of the continuous steel casting process these boundary conditions may be declared in three various ways. The equation below describes the second- (the Neumann condition) and the third-type boundary conditions [11]:

$$Q = Flux + \alpha\left(T - T_{\alpha}\right) + \sigma\varepsilon\left(T^4 - T_{\alpha}^4\right) \tag{3}$$

where $Flux$ is heat flux, W m^{-2}; α is heat transfer coefficient, W m^{-2} K^{-1}; T_a is ambient temperature, K; σ is the Stefan-Bolzmann constant, W m^{-2} K^{-4}; ε is emissivity. The heat flux may be defined in the model directly as the $Flux$ value (the Neumann condition), as well as with the convection (α – substitute heat-transfer coefficient), and with the radiation models (ε – emissivity). In each case – when defining the boundary conditions – the ambient temperature T_a should be indicated. The surfaces for which boundary conditions were introduced were broken down into four groups:

1. The contact of the solidifying strand surface with the inner side of the mould
2. The mould outer side
3. The surface of the liquid steel meniscus
4. The secondary cooling zone

In the numerical model of the continuous steel casting process, the primary cooling zone was divided into two main areas, for which the heat transfer coefficients were calculated. Calculating the heat transfer coefficient, with water-cooling in the mould channels based on the available formulas, is complex because of the method of heat transfer to the water flowing through the channel. To determine the average heat transfer coefficient, the following formula may be applied for the outer surface of the mould [9,12]:

$$\alpha_W = \frac{Nu\lambda_w}{d_k} x_k \tag{4}$$

where Nu is the Nusselt number; λ_w is the thermal conductivity for the cooling water W m^{-1}K^{-1}; x_k is the share of water-cooled mould area; d_k is the cooling channel diameter, mm. The value of the heat transfer coefficient of 24000 W m^{-2}K^{-1} was calculated, corresponding to the value of the heat received by the water flowing in the mould channels. This value was implemented on the outer walls of the mould. For the solidifying strand surface contacting with the mould wall, the heat transfer coefficient was calculated as a function of strand surface temperature. The calculated values were in the range of 860-1600 W m^{-2}K^{-1}. The heat transfer coefficient achieves its maximum value when the heat is transferred from the liquid steel to the mould. Below the solidus temperature, the heat transfer in the gap consists of the conduction fading with a decline in the strand surface temperature, the gap development, and the transformation of the mould powder into the solid state. In the model of the heat transfer in the gaseous gap, two basic heat transfer mechanisms – by radiation and by conductivity – were assumed. For the secondary cooling zone, based on the numerical values of the water flux density, a set of heat transfer coefficients was calculated for each of the spray zones. Dependence 5 was used to determine the heat transfer coefficient for each of the spray zones [8,12]:

$$\alpha = 10v + (107 + 0.688v)\, w \tag{5}$$

where α is heat transfer coefficient, W m^{-2} K^{-1}; v is water drops‘ velocity, m s^{-1}; w is water flux density, dm^{3}m^{-2}s^{-1}.

3. Results of numerical calculations

The numerical calculations were performed for three strand casting speeds: 0.6, 0.8 and 1 m min^{-1}, along with an appropriate set of heat transfer coefficients which were calculated on the basis of industrial data. Selection of the casting speed was determined by the actual casting speeds of S235 grade heats. Table 2 and Figure 2 present three sets of heat transfer coefficients for each of the spray zones. Sets of heat transfer coefficients were calculated based on water flux density values for each of the spray zone, according to the dependence 5.

TABLE 2

The values of heat transfer coefficients for the spray zones at various speeds

	Spray zones						
	1	2	3	4	5	6	7
	Heat transfer coefficient/W m^{-2}K^{-1}						
0.6 m min^{-1}	600	420	440	270	160	140	110
0.8 m min^{-1}	860	470	500	320	240	210	160
1 m min^{-1}	880	480	530	320	240	210	200

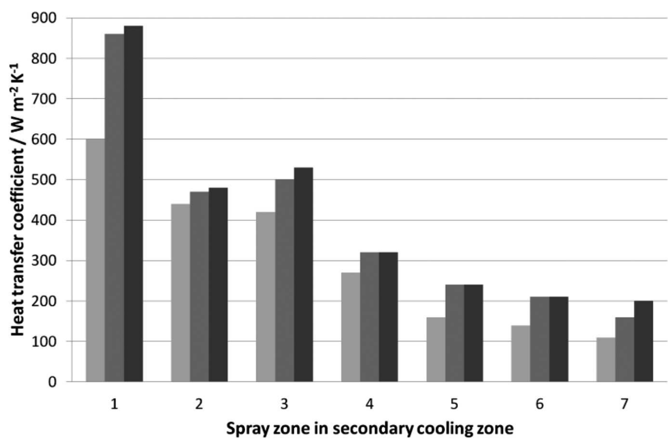

Fig. 2. The values of heat transfer coefficients for the spray zones at various speeds

The numerical calculations for the three casting speeds were verified based on the analysis of:

1. The thickness of the shell leaving the mould.
2. The metallurgical length.

3. The temperature distribution on the strand surface and the comparison of the calculated temperature values at the measurement points.

Table 3 presents the thickness of the shell leaving the mould and the metallurgical length for the three casting speeds examined. The values in Table 3 were calculated using the numerical model of the continuous steel casting process.

TABLE 3

The metallurgical length and the shell thickness under the mould for three speeds examined

	Casting speed/m min^{-1}		
	0.6	0.8	1
Metallurgical length/m	9.1	12.92	16.73
Thickness of the shell after leaving the mould/cm	2.85	2.66	2.51

For the speed of 1 m min^{-1}, the thickness of the shell under the mould was 2.51 and the metallurgical length was 16.73. The above values conform with values introduced as a solidification model provided by SMS Demag – producer of the CC machine. For the speed of 1 m min^{-1}, there was no difference for the shell thickness between the author's own calculations and the solidification model provided by SMS Demag. For the metallurgical length the difference was equal 0.7 m. For the speed of 0.8 m min^{-1}, the difference between the author's own calculations and the manufacturer's guidelines for the shell thickness was 1 mm; for the metallurgical length this was 1 m. The discrepancies were greatest for the speed of 0.6 m min^{-1}, 2 mm for the shell thickness, and 1.2 m for the metallurgical length. The thickness of the solidified strand layer could be also determined by a simplified method with the different mathematical formulas. [10] However, the use of more complex models with thermal properties and dimension of the CC model, is more likely to give correct results.

The next step in the verification process of the calculations made – using the numerical model of the continuous steel casting process – was comparing the temperature values at the reference points. The first measurement point was located at a distance of about 2.5 m under the mould. For the first reference point, the temperature values that were calculated with the numerical model were compared to the values measured with pyrometers during the industrial tests. The values of the strand surface temperature – calculated with the numerical model – showed an excellent level of compliance with the values of temperatures measured during the tests conducted. Similarly, for the second measurement point (about 18 m after leaving the secondary cooling chamber), the calculated values of the strand surface temperature were compared to the temperature values recorded by a pyrometer which was permanently installed at the continuous casting machine examined. The values of the strand surface temperature calculated with the numerical model of the continuous casting process, and the values measured with the optical pyrometer, are presented in **Table 4**.

The foregoing results confirmed a very high rate of accuracy in the calculation of the formulated numerical model of the steel continuous casting process.

4. Determining new cooling parameters within the secondary cooling zone

The results of numerical simulations clearly indicate that the metallurgical length is the parameter that is characterised by the biggest discrepancy of the calculated values (at various casting speeds). The difference in the metallurgical length can be observed both in the manufacturer's recommendations and in the results of numerical simulations obtained with the proprietary numerical model of the continuous process of steel casting. Maintaining a comparable metallurgical length for various strand casting speeds guarantees that safety is ensured during the continuous casting process because the strand is wholly solidified before shearing. It has been found that for the continuous caster examined, the best area where the total solidification of the strand should occur is the area before the exit from the secondary cooling chamber. It is related to the location of the soft reduction zone and the location of the last point of strand straightening. The metallurgical length should be achieved between the eighth and ninth segment of the casting machine, or between 16 m and 18 m of the machine length. Based on the data recorded during the completed industrial tests, the influence of a change in the strand casting speed, resulting in changes in the flows of cooling water in the individual spray zones, was analysed. The first step of

TABLE 4

The values of the strand surface temperature calculated and measured at the reference points

Casting speed / m min^{-1}	0.6		0.8		1	
Temperature /°C	The average measured temperature	The calculated temperature	The average measured temperature	The calculated temperature	The average measured temperature	The calculated temperature
First measurement point	835	840	845	854	855	861
Second measurement point	850	854	875	867	910	912

the proposed method for determining the new cooling values is to calculate the influence of a change in the strand withdrawal speed on the metallurgical length, while verifying the shell thickness and the temperature at the reference points. The sensitivity analysis of the numerical model of the continuous steel casting process as regards the casting speed will allow the determination of the percentage impact of a change in only the casting speed on the metallurgical length. Knowing this dependence will allow the calculation of the influence of a change in the cooling parameters, which must always be correlated with the casting speed.

4.1. Calculation of the impact of a change in the casting speed on the metallurgical length

For the secondary cooling zone, a test set of heat transfer coefficient values was assumed: 770, 700, 300, 200, 160, 140, 110 $Wm^{-2}K^{-1}$ for the seven spray zones respectively. An increase in the speed by 0.2 m min^{-1} caused an extension of the metallurgical length by about 4 m. For the change in speed from 0.6 to 0.8 m min^{-1}, the obtained metallurgical length was longer by 50%. The subsequent change in speed from 0.8 to 1 m min^{-1}, caused an increase in the metallurgical length by 30%. The simplest method of determining the new cooling values for the spray zones is by the percentage change of individual heat transfer coefficients, taking into account the percentage change in the metallurgical length as a function of the casting speed. The described method is an effective approach from a numerical perspective. However, determining the new sets of cooling values must be correlated with the existing process. In addition the relationships of changes in the water flow rates for individual spray zones must be maintained. For determining the new values of heat transfer coefficients, the changes that were applied for the heat transfer coefficients within the first two cooling zones were the smallest, while more significant changes were introduced within the other spray zones, at the same time the temperature increase within the spray zones was controlled. Such an approach is extremely important for maintaining the safety of the continuous steel casting process.

4.2. Determining the new heat transfer coefficients within the secondary cooling zone

For the speed of 1m min^{-1}, the set of cooling factors was unchanged because the desired values of the metallurgical length, the temperature at the reference points, and the shell thickness after leaving the mould were obtained. The simulation for the speed of 1 m min^{-1} was considered the reference for further considerations. The starting point in the algorithm presented were the heat transfer coefficients for the seven spray zones; these were calculated based on the actual flows of water for the three speeds examined. **Figure 3** presents the diagram of the algorithm for determining the new values of heat transfer coefficients.

One mean heat transfer coefficient for the whole secondary cooling zone $\alpha_{average}$ was calculated, based on the heat transfer coefficients calculated for the spray zones, using the proposed dependence presented in the formula below:

$$\alpha_{average} = \frac{\sum_1^n \alpha_n s_n}{\sum_1^n s_n} \tag{6}$$

where α_n is the heat transfer coefficient for each spray zone, $Wm^{-2}K^{-1}$; s_n is the area of the spray zone, n is the number of a spray zone. The mean heat transfer coefficient for the secondary cooling zone was calculated from the dependence 5. This was: 305, 395 and 410 $Wm^{-2}K^{-1}$, for the speed of 0.6, 0.8 and 1 m min^{-1} respectively. Being aware of the percentage impact of the casting speed on the metallurgical length, the new heat transfer coefficient for the secondary cooling zone was calculated for the speeds of 0.6 and 0.8 m min^{-1}, for which a similar metallurgical length would be obtained as for the speed of 1 m min^{-1}. The following dependence was used [10]:

$$\alpha'_{average} = \frac{\alpha_{average}}{k} \tag{7}$$

where k is the coefficient based on the percentage relationship of the metallurgical length as a function of casting speed. The new heat transfer coefficient for the secondary cooling zone was calculated from the dependence 6. For the speed of 0.8 m min^{-1} the average heat transfer coefficient should be 315 $Wm^{-2}K^{-1}$, and for the speed of 0.6 m min^{-1} the average heat transfer coefficient should be about 205 $Wm^{-2}K^{-1}$. The numerical calculations conducted for the new, mean values of the heat transfer coefficient for the secondary cooling zone $\alpha'_{average}$ have confirmed the above method was correct. Similar metallurgical lengths of 15.7 m and 16.5 m were obtained for the speeds of 0.6 and 0.8 m min $^{-1}$ respectively. At the next stage, the heat transfer coefficient was calculated with dependence 5 for each spray zone. The calculations resulted in a few sets of heat transfer coefficients. The values of heat transfer coefficients that met the boundary conditions in the form of the admissible percentage change in the heat transfer coefficients in the individual spray zones were selected. The boundary conditions were determined based on the actual change in the flows of cooling water in the spray zones for a selected speed. **Table 5** presents the new values of heat transfer coefficients for two casting speeds examined.

TABLE 5

New values of heat transfer coefficients

	Spray zones						
	1	2	3	4	5	6	7
	Heat transfer coefficient, $Wm^{-2}K^{-1}$						
0.6 m min^{-1}	440	400	210	100	100	100	90
0.8 m min^{-1}	650	430	350	200	180	160	150

For the cooling coefficient values presented in **Table 5**, numerical calculations were performed with the verified model of the continuous casting process. This allowed a preliminary evaluation of the correctness of the considerations presented above. For the speed of 0.6 m min^{-1} a metallurgical length of 15.5 m was obtained, whereas for the speed of 0.8 m min^{-1} the metallurgical length was 16.3 m. Also, the temperature at the selected points was monitored. As expected, the reduction of cooling in the individual spray zones caused an increase in the temperature on the strand surface. The results of the calculated temperatures are presented in **Table 6**.

TABLE 6
The values of temperature at the reference points for the new values of heat transfer coefficients

Casting speed, m min^{-1}	The calculated temperature under the mould, °C	The calculated temperature at the first measurement point, °C	The calculated temperature at the second measurement point, °C
0.6	848	1070	890
0.8	862	970	950

For the new values of heat transfer coefficients the safe shell thickness that was measured immediately under the mould was maintained. The biggest change in the strand surface temperature was calculated for the third and fourth spray zone. As already mentioned, it is possible to calculate the heat transfer coefficients based on the cooling water flow rates within the individual spray zones. The applied calculation method enables the calculation procedure to be reversed and the cooling water flow rate $dm^3 min^{-1}$ to be determined based on the heat transfer coefficients. For the new heat transfer coefficients the water flow rates were calculated for the individual spray zones. The values are presented in **Table 7**.

TABLE 7
The new values of flow rates for the spray zones calculated on the basis of the new heat transfer coefficients

	Spray zone						
	1	2	3	4	5	6	7
	Water flow rate, $dm^3 min^{-1}$						
0.6 m min^{-1}	70	56	200	150	150	150	100
0.8 m min^{-1}	110	65	420	300	170	154	100

Based on the determined values of the cooling water flow rate, $dm^3 min^{-1}$ the cooling programme correlated with the S235 steel grade cast may be modified.

5. Conclusions

1. The formulated numerical model of continuous casting of steel, based on the input parameters calculated on the basis of industrial data, allows calculation of a reliable strand temperature distribution in the process of the continuous casting of steel.
2. The conducted model verification allows us to accurately determine the metallurgical length of the strand cast and the shell thickness under the mould. It was revealed that changes in both mentioned parameters depend on the casting speed in a non-linear way.
3. A solution was proposed to maintain a constant metallurgical length during the continuous casting process, regardless of the grade cast and the casting speed. The area within the secondary cooling chamber in which the strand should totally solidify was determined accurately as a matter of continuous casting process safety, along with the location of the *soft reduction* zone and the permanent strand straightening points.
4. An algorithm for calculating heat transfer coefficients for the secondary cooling zone was formulated, also allowing the determination of the flow rate in the individual spray zones.
5. It is possible to use the formulated numerical model of the continuous steel casting process to determine new values of heat transfer coefficients for the spray zones, and the developed method allows the calculation of the cooling water flow rate dm^3 min^{-1} in the spray zones based on heat transfer coefficients $Wm^{-2}K^{-1}$.
6. The formulated numerical model of the continuous casting process may be applied to change other process parameters e.g. to determine the safe change in the strand casting speed.

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