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STRATEGY OF COOLING PARAMETERS SELECTION IN THE CONTINUOUS CASTING OF STEEL

This paper presents a strategy of the cooling parameters selection in the process of continuous steel casting. Industrial tests were performed at a slab casting machine at the Arcelor Mittal Poland Unit in Krakow. The tests covered 55 heats for 7 various steel grades. Based on the existing casting technology a numerical model of the continuous steel casting process was formulated. The numerical calculations were performed for three casting speeds – 0.6, 0.8 and 1 m min^{-1}. An algorithm was presented that allows us to compute the values of the heat transfer coefficients for the secondary cooling zone. The correctness of the cooling parameter strategy was evaluated by inspecting the shell thickness, the length of the liquid core and the strand surface temperature. The ProCAST software package was used to construct the numerical model of continuous casting of steel.

Keywords: continuous casting of steel, cooling parameters, numerical modelling

1. Introduction

Continuous casting is the last stage of the steel production process. It is a modern, prevailing and continuously developing process of steel semi-product casting. The development of the steel continuous casting primarily serves the improvement of the production process by improving the quality of the steel products.[1-11] The cooling water flow rate in individual cooling zones of the continuous casting machine, which is correlated with the cast strand casting speed, is one of the most important process parameters. Due to the need to cast new steel grades, it is necessary to develop a strategy for the selection of cooling parameters. The correct selection of the strand cooling parameters is key to the casting process and extremely difficult due to the complex nature of the steel solidification process and the accompanying effects.[12]

In order to develop a strategy for the selection of the cooling parameters for the selected continuous casting machine it was necessary to carry out industrial tests. The slab continuous casting machine operating in the Krakow Branch of Arcelor Mittal Poland was selected for analysis. In the first step, the continuous casting machine was analysed for the technology, and subsequently, 9 sequences were covered with tests, including 55 heats for 7 various steel grades. The obtained test heat database in the industrial production conditions included 52 parameters controlling the steel continuous casting process. Details concerning cooling water flows in the individual spray zones (including water temperature and pressure), along with the formulated models of heat transfer in the continuous steel casting process, allowed reliable heat transfer coefficients to be computed for individual cooling zones. Additional temperature measurements of the strand surface were made with a two-colour pyrometer and a thermovision camera. The optical pyrometer was installed on the subsequent segments of the continuous casting machine, depending on the sequence tested, which allowed us to obtain a few reference points for the strand surface temperature. A thermovision camera was used to identify the temperature distribution in a wider area compared to the spot pyrometer reading. The thermovision camera was installed downstream of the last segment of the continuous casting machine.

Based on the existing casting technology for the continuous caster selected for this study, a numerical model of the process was formulated that allowed the temperature distribution within the whole volume of the solidifying strand to be computed. Actual, measured and verified values including material parameters, boundary conditions and preliminary conditions were implemented in the model. The correctness of the cooling parameter strategy was evaluated by inspecting the shell thickness, the length of the liquid core and the strand surface temperature in the reference points.

2. Primary cooling zone

Describing the heat transfer model in the primary cooling zone is a complex task as all three mechanisms of heat transfer occur - conduction, radiation and convection.[6,10,12] The following processes influence the heat transfer in the mould: the conduction and convection in the liquid steel area, the conduction in the solidified shell, the heat transport between the outer layer of the solidified shell and the mould wall surface through an air gap forming in the mould, and the heat conduction in the mould. The correct description of the effect of the air gap formation immediately after the steel has cooled to the solidus temperature, under the liquid steel meniscus surface, is an additional difficulty. The oscillatory movement of the mould and, in addition, the strand movement in the mould

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with a variable casting speed, strongly influence the actual dimensions of the gap. Additionally, thermal effects related to the accompanying phase transformations have a significant influence on the heat transfer model. It should be emphasised that during continuous casting the most intensive heat transfer occurs at the height of the liquid steel meniscus in the mould. The heat flux density in this area reaches values of 1.5 - 5.5 M W m $^{-2}$. In terms of numbers it corresponds to the heat transfer coefficient value from 1000 to 2500 W m^{-2} K^{-1}.[12]

In the formulated model, the heat is transferred between the cast strand and the mould through the gap. The heat transfer area in the mould is divided into two zones. In the first one no gaseous gap is assumed. The whole space between the strand and the mould is filled with the mould powder. As a result of metal contraction, a gaseous gap develops at a certain distance from the meniscus. This gap separates the mould powder layer from the mould surface, additionally insulating the strand. A change in the heat transfer coefficient is related to the assumed point of the air gap formation. Figure 3 presents a diagram of thermal resistances in the formulated model.[12-14]

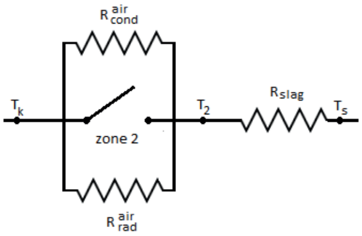

Fig. 1 Diagram of the thermal resistances [12-14]

In the model of the heat transfer in the gaseous gap, two basic heat transfer mechanisms – by radiation and by conductivity [14] were assumed. The heat transfer coefficient between the strand surface and the mould h is:

$$\mathrm{h} = \frac{1}{\mathrm{R}_{sk}} \tag{1}$$

where:

$$R_{\mathrm{sk}} = R_{\mathrm{air}} + R_{\mathrm{slag}} \tag{2}$$

$$\frac{1}{\mathrm{R_{air}}} = \frac{1}{\mathrm{R}^{air}_{\mathrm{cond}}} + \frac{1}{\mathrm{R}^{\mathrm{air}}_{\mathrm{rad}}} \tag{3}$$

$$R_{slag} = \frac{\mathrm{d_{slag}}}{\lambda_{\mathrm{slag}}} \tag{4}$$

where R_{air} is heat resistance of the air gap in the mould, m^2 K W^{-1} ; R_{slag} is heat resistance of the mould powder, m^2 K W^{-1}; R^{air}_{cond} is conduction thermal resistance in the mould, R^{air}_{rad} m^2 K W^{-1}; - radiation thermal resistance in the mould, m^2 K W^{-1}. The values of heat transfer coefficients within the model were subject to verification. The limit value of the heat transfer coefficient is the criterion that allows determining whether the assumed heat transfer coefficient in the mould-strand system is correct. It is obtained from the energy balance in the primary cooling system, which is based on the results of measurements of the increase in temperature and the volumetric flow rate of the cooling water in the continuous casting machine mould. This paper assumes a maximum value of the heat transfer coefficient of 1600 W m $^{-2}$ K $^{-1}$. [5,13,14] A change in the heat transfer coefficient is related to the assumed point of the air gap formation. The value of the heat transfer coefficient was implemented as the function of solidifying cast strand surface temperature. The value of the heat transfer coefficient on the outer mould walls was assumed at 24000 W m^{-2} K^{-1}. [5,13,14] It is a value corresponding to the heat absorption directly effected by the cooling water flowing in the mould channels. This value is related to the shape and volume of the mould channels in relation to the total volume of the mould.

3. Secondary cooling zone

After leaving the mould the slab surface is cooled with a water spray and by air. The heat flux that is carried away from the surface of the solidifying strand is proportional to the temperature difference between the strand surface and the cooling medium temperature. In this zone it is recommended to maintain the cooling intensity, thereby leading to gradual temperature changes. It allows avoiding cracks generated by thermal stresses. [12] The heat exchange with the environment is accompanied by a few mechanisms: the direct impact of the water stream on the strand, cooling with water flowing down the surface and with reflected drops, cooling by water lying over a roll in a formed cavity, cooling with the ambient air at places located directly over a roll, cooling through contact faces with a roll.

Heat absorption from the surface of the solidifying strand is a complex process due to the nature of the heat exchange accompanying the boiling effect. When the surface of the strand leaving the mould is cooled, film boiling prevails. At this stage, the main mechanism of heat transfer is conduction through the vapour film resulting from the supply of water to the hot surface of the strand via nozzles. The heat transfer mechanism is also accompanied by radiation, therefore, the lower the strand surface temperature, the lower the value of the heat transfer coefficient. The water drop momentum is highest at the centre of the cooling area, it enables the vapour film to be broken and allows direct contact between the water and the strand surface cooled. It intensifies the cooling process in this area, therefore the amount of heat received strongly depends on the liquid velocity. During further cooling, as the temperature drops below the Leidenfrost point, a transition boiling effect occurs. It causes an increase in the heat transfer coefficient.[12] During further cooling we observe the effect of bubble boiling, along with a further decline in the heat transfer coefficient. After the end of the bubble boiling stage and cessation of conditions for vapour forming, the strand surface is cooled by forced convection.

If the solidifying strand surface temperature is not known, a simplified formula may be applied to calculate the heat transfer coefficient for the individual spray zones. Based on the numerical values of the water flux density, a set of heat transfer coefficients was calculated for each of the spray zones within the secondary cooling zone. Dependence 5 was used to determine the heat transfer coefficient for each of the spray zones [12-14]:

$$\alpha = 10v + (107 + 0{,}688v)w \tag{5}$$

where α is heat transfer coefficient, W m^{-2} K^{-1}; v is water drops' velocity, m s^{-1}; w is water flux density, $dm^3m^{-2}s^{-1}$. Formula 5 could be used for water flux from 0,3 to 9,0 dm^3 m^{-2} s^{-1} and water drops' velocity from 11 to 32 m s^{-1}.

4. Strategy of the cooling parameters selection

The correct selection of strand cooling parameters in the continuous casting machine should be based on a simultaneous meeting of the following criteria:

- Total solidification of the cast strand should occur in the soft reduction zone.
- The shell thickness under the mould should ensure a failure-free casting process (no leakages and strand breakout).
- Thermal stresses in the cast strand should not cause an occurrence of defects in the form of cracks.
- The cast strand structure should ensure that it is correctly processed at the hot rolling mill.

At present, finding a universal method that meets all the listed criteria is a very complex task. 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. 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. [2-4,15-18] Assuming that a numerical model of the steel continuous casting process is used for this purpose, one should note that the model form strongly depends on the problem that we want to solve with this model. In the *ProCAST* package, the metallurgical length of the strand and the shell thickness under the mould may be calculated with the thermal or *thermal + flow* models. The *MILE* module is required to be used for determining the stress values. The internal structure of a strand may be simulated with the *CAFE* module.

From the process point of view, the issue of strand cooling parameter selection may be divided into two areas:

- The selection of cooling parameters for casting a new steel grade assuming the optimal casting speed.
- The selection of cooling parameters for a defined steel grade including an option of variable casting speed.

The latter should enable the full automation of the casting process and ensure the correct change in the cooling intensity at each change of the strand drawing speed. Due to the dynamics of the casting process at the continuous casting machine, the control of the machine as regards the cooling intensity must be always on-line. The information set concerning the strand cooling intensity in the individual machine zones related to the casting speed is called cooling curves. During a purchase of a continuous casting machine, the manufacturer always supplies a database with cooling curves of the selected groups of steel cast in the specific steel plant. The knowledge of the method of creation of the database with cooling curves is essential both for implementing new steel grades for production, and for evaluating the correctness of the casting process of other grades already in the product range.

The proposed strategy of the cooling parameter selection is based on checking all criteria listed in the introduction. In the submitted paper the first two criteria will be discussed, in particular the effect of the allowable process parameter alterations on the change in strand metallurgical length and shell thickness under the mould.

Previous papers [13] presented a method for determining new values of the heat transfer ratios α in the individual secondary cooling zones, forced by the need to change the metallurgical length. The algorithm of this procedure is shown graphically in Fig. 2.

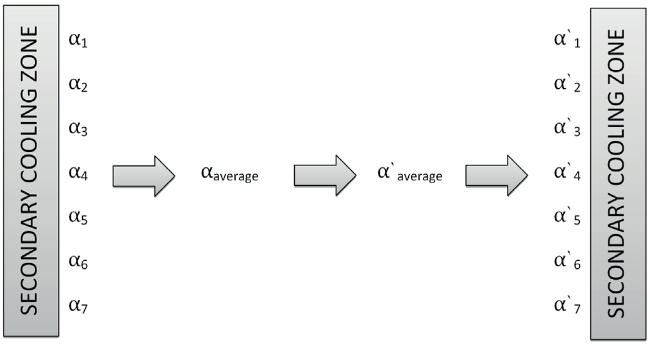

Fig. 2. The diagram for calculation of new heat transfer coefficients [13]

The average values α and α' are determined according to the following equations:

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

and

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

where αn is the heat transfer coefficient for each spray zone, W m^{-2} K^{-1}; sn is the area of the spray zone, n is the number of a spray zone; k is the coefficient based on the percentage relationship of the metallurgical length as a function of casting speed. In order to show the influence of the variable value of heat transfer coefficients in the individual secondary cooling zones, calculations made on the basis of the recorded values of a S235 slab cooling intensity will be presented. A simulation was performed for each of the three casting speeds, where average values of cooling intensity in each of seven spray zones were assumed. In addition, for the standard casting speed, which, for the cast strand format and the steel grade concerned, was 1 m min^{-1}, the metallurgical length was calculated for the minimum and maximum value of the cooling water flow rate. In each of the presented cases, the pattern for defining the boundary conditions was as follows.

4.1. Boundary conditions

For each of the seven spray zones, the mean heat transfer coefficient was calculated on the basis of the cooling water flux density. The water flow rate, 1 min^{-1}, at the current casting speed was read from the database collected during the test heats. The water flux density was calculated on the basis of the cooling water flow rates and the size of the individual spray zone. The heat transfer coefficients were calculated for each of the seven spray zones with dependence 5 and the water flux densities. The minimum, maximum and mean values of the water flow rate in the individual spray zones for three recorded casting speeds (0,6; 0,8; 1 m min^{-1}) were analysed. Table 1 presents the minimum and maximum flow rates of the cooling water in the individual spray zones for three main casting speeds for steel S235.

Based on the values presented in the table, the values of heat transfer coefficients were calculated for each of the spray zones.

In addition, for the air-cooled zone, one, constant value of heat transfer coefficient of 86 W m^{-2} K^{-1} was calculated which was independent of the casting speed.

4.2. Numerical simulations

The temperature field calculations, based on the formulated mathematical model of the continuous steel casting process, were made with the *ProCAST 2014* software package. 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 selection of the casting speed was determined by the actual speeds of casting S235 grade heats for the sequence investigated. By analysing the database of parameters controlling the continuous casting process, it was found that the maximum and minimum values of water flow rates in the spray zones were mainly related to speed variations during the sequence. Water flow rates were growing along with an increase in the casting speed and, similarly, the water flow rates were decreasing along with a reduction in the casting speed. The most frequently occurring flow rates for water flowing through the individual spray zones were used for the calculations. This allowed the most representative water flow rate values in the individual zones to be obtained. The beginning and the end of a sequence was not taken into

TABLE 1

The minimum and maximum flow rates of the cooling water in the spray zones for three casting speeds

Spray zone	Casting speed, m min^{-1}					
	0.6		0.8		1	
	Cooling water, l min^{-1}					
	MIN	MAX	MIN	MAX	MIN	MAX
1	57,42	139,06	116,02	144,92	158,20	191,41
2	46,88	57,72	48,93	71,19	63,14	89,65
3	470,98	683,00	441,80	749,00	332,61	445,59
4	431,83	571,47	373,83	616,59	330,86	373,83
5	287,11	342,03	246,09	384,52	260,00	277,58
6	0,00	157,71	0,00	267,08	4,40	5,86
7	14,89	20,02	8,30	13,18	16,11	17,09

TABLE 2

The minimum and maximum values of heat transfer coefficient in the spray zones

Spray zone	Casting speed, m min^{-1}					
	0.6		0.8		1	
	Heat transfer coefficient, W m^{-2} K^{-1}					
	MIN	MAX	MIN	MAX	MIN	MAX
1	412	784	679	811	871	1022
2	358	406	367	466	431	548
3	378	481	364	513	311	366
4	262	298	247	310	236	247
5	215	227	205	237	209	212
6	0	186	0	212	151	151
7	154	156	152	154	155	155

account to calculate the heat transfer coefficient sets on the basis of flow rates.

Note, that casting in accordance with the applicable process instruction, in the case of casting speed reduction, leads to a significant reduction in cast strand metallurgical length. For casting speeds of 0.6, 0.8 1 m min^{-1} it is 9.1, 12.92 and 16.73 m respectively. In the case concerned, the level of the metallurgical length reduction seems too large, but it partially results from the process safety requirements. The information on the hypothetical change in the metallurgical length of the strand is interesting, assuming that the casting process is conducted at the minimum and maximum values of the cooling water streams. The calculation results are presented in Table 3.

TABLE 3
The metallurgical length and the shell thickness under the mould for three cooling variants

Casting speed = 1 m min^{-1}	Cooling water, l min^{-1}		
	MIN	MAX	Average
Metallurgical length, m	17.2	14.4	16.7
Thickness of the shell after leaving the mould, cm	2.48	2.62	2.51

The simulation result obtained in table 3 indicates that the stability of the strand cooling conditions is very important and the water flow in both cooling zones needs to be fully controlled.

5. Conclusions

The analysis of the experiments carried out in industrial conditions and the results of numerical simulation of the cast strand solidification process for experimental heats allow us to draw the following conclusions:

1. Full control of the steel continuous casting process requires access to tools allowing the cooling curves to be correctly determined.
2. The most important tool for creating a cooling curve is a correctly formulated and well- verified numerical model of the continuous casting process.
3. The variability of the cooling water flux value for a set casting process, occurring in practice, may cause problems with the product quality. This is also indicated by the spread of the obtained metallurgical length calculated hypothetically for the minimum and maximum stream values.
4. The cast strand metallurgical length should allow the strand to solidify totally within the soft reduction zone. The selection of cooling parameters should guarantee the required solidification, regardless of the casting speed.
5. The thickness of the shell under the mould should ensure sufficient mechanical strength of the strand.
6. The calculated metallurgical length and shell thickness under the mould, for average water flow rate values in the individual spray zones, indicate that the presented strategy for selecting the continuous steel casting process cooling parameters is right.
7. Work will be continued towards evaluation of the stresses occurring in the shell and the structure of the forming cast strand. It will allow the third and fourth criterion defined in the study to be taken into account for the selection of cooling parameters.

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