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OPERATIONAL EXPERIENCES WITH THE OPTIMIZATION OF SECONDARY COOLING

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Abstract

Surface temperatures of cast slabs at small radius segments in front of as well as at the unbending point belong to parameters that affect the surface quality of continuously cast slabs. Older machines for continuous casting were designed with regard to the performance (to amount of cast slabs) rather than to the quality. Therefore, the adaptation of secondary cooling is required in order to accomplish the desired surface temperatures. The modification consists in the dynamic control of secondary cooling, surface temperatures monitoring by means of the numerical model of temperature field as well as in a prospective replacement of cooling nozzles. The paper deals with relationships of described influences and their impacts to the temperature field of cast slabs. The results are presented for the 1530x250 mm slabs that are cast in Evraz Vítkovice Steel where the main author's dynamic 3D solidification model is used to control the production. The results and experiences obtained after the replacement of cooling nozzles are compared to long-time operational data for the preceding setup of cooling nozzles. The comparison is performed with the use of data acquired from the dynamic solidification model and with the use of the statistical operational data.
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Keywords

optimization of temperature field, surface temperature, cooling of nozzles

1. Introduction

The presented in-house model of the transient temperature field of the blank from a slab caster (Fig. 1) is unique in that, in addition to being entirely 3D, it can work in real time. The numerical model covers the temperature field of the complete length of the blank (i.e. from the meniscus inside the mould all the way down to the cutting torch) with up to one million nodes [1].

The concasting machine (caster) for the casting of slabs (Fig. 1) has the secondary-cooling zone subdivided into thirteen sections, due to the convection of a greater amount of heat from the voluminous slab casting. The first section engages water nozzles from all sides of the slab. The remaining twelve sections engage air mist cooling nozzles, which are positioned only on the upper and underside of the concasting. It is therefore very important to determine the correct boundary conditions for the numerical model of the temperature

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field [2]. Regarding the fact that on a real caster, where there are many types of nozzles with various settings positioned inside a closed cage. Real caster contains a total 8 types of nozzles and geometrical layouts. The aim is to modify the secondary cooling zones 6, 8 and 10 so as to increase the surface temperature of the slab in a small radius at point of straightening. Currently in cooling zones 6, 8 and 10 nozzles installed air mist nozzles Lechler 100.638.30.24 (Fig. 2).

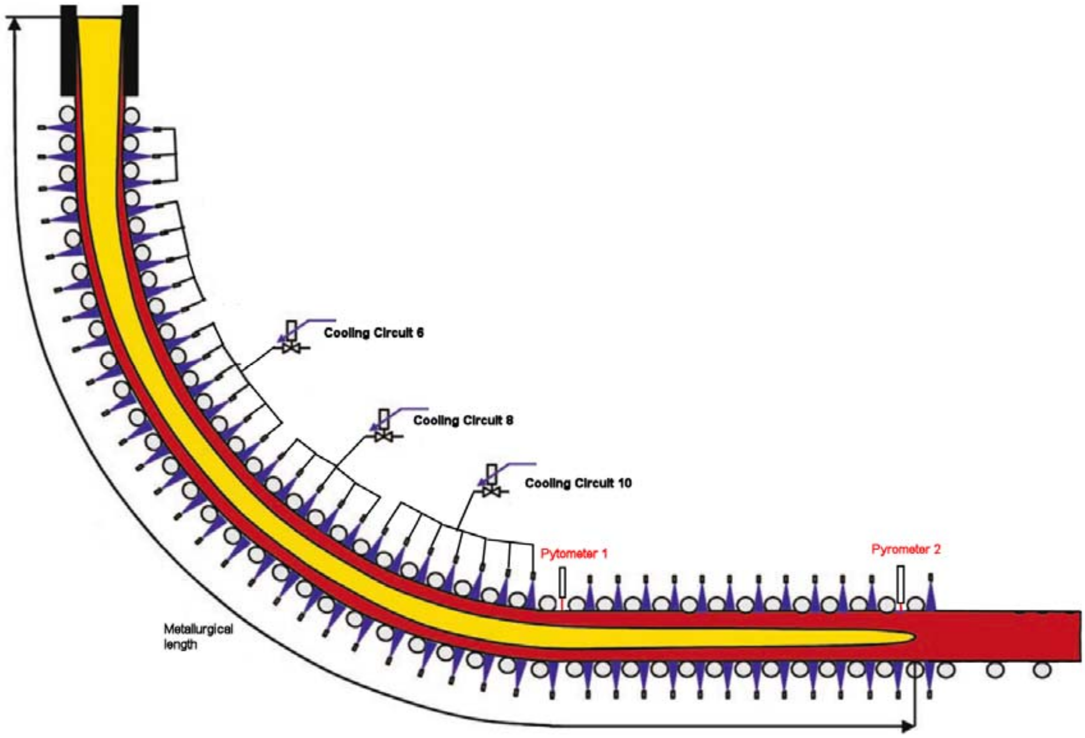


Fig. 1 Radial caster with cooling circuit and position of pyrometers

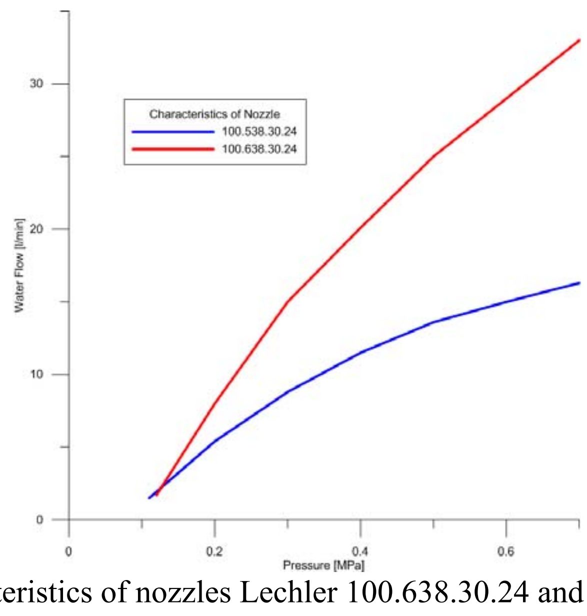


Fig. 2 Characteristics of nozzles Lechler 100.638.30.24 and 100.528.30.24

2. The heat transfer coefficient of the nozzle

The cooling by the air mist water nozzles has the main influence and it is therefore necessary to devote much attention to establish the relevant heat transfer coefficient (*HTC*) of the forced convection. Commercially sold models of the temperature field describe the heat-transfer coefficient beneath the nozzles as a function of the incident quantity of water per unit area. They are based on various empirical relationships. This procedure is undesirable. The model discussed in this paper obtains its heat transfer coefficients from measurements of the spraying characteristics of all nozzles used by the caster on a so-called hot plate in an experimental laboratory and for a sufficient range of operational pressures of water and a sufficient range of casting speeds of the slab (i.e. casting speed). This approach represents a unique combination of experimental measurement in a laboratory and a numerical model for the calculation of the non-linear boundary conditions beneath the cooling nozzle.

This laboratory device enables the measurement of each jet separately. It comprises a steel plate mounted with 18 thermocouples, heated by an external electric source. The steel plate is heated to the testing temperature, than it is cooled by a cooling jet. On the return move the jet is covered by a deflector, which enables the movement of the jet without cooling the surface. This device measures the temperatures beneath the surface of the slab–again by means of thermocouples [3]. The laboratory device allows the setting of:

- The nozzle type.
- The flow of water.
- The air-pressure.
- The distance between the nozzle and the investigated surface.
- The surface temperature.
- The shift rate (casting speed).

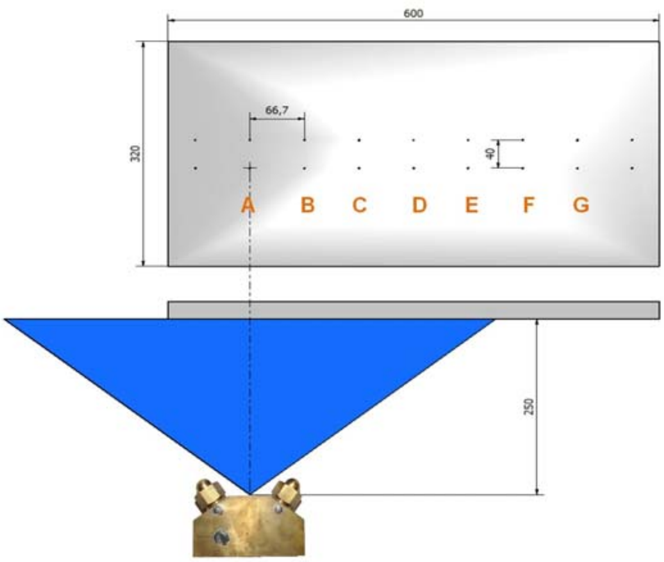


Fig. 3 Diagram of measurement configuration of the cooling effects of nozzle

Since the cooling nozzle 100.638.30.24 for minimum water flow appears to be too intensive and measurements were made for such a small nozzle 100.528.30.24 (Fig. 3). Based on the temperatures measured in dependence on time, the HTCs are calculated by an inverse task. They are then processed further using an expanded numerical and an identification model and converted to coefficients of the function *HTC*(T,y,z) (Fig. 4), which expresses the *HTC* in dependence on the surface temperature, and also the position of the concasting with respect to the nozzle. The Lechler air mist nozzles have low dependence of heat transfer coefficient on the slab surface temperature. The value of the *HTC* on the surface of the slab, as it enters the secondary-cooling zone, significantly affects the process simulation from the viewpoint of the temperature field, the technological length, and also other technological properties. It therefore affects prediction of the quality of the slab.

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

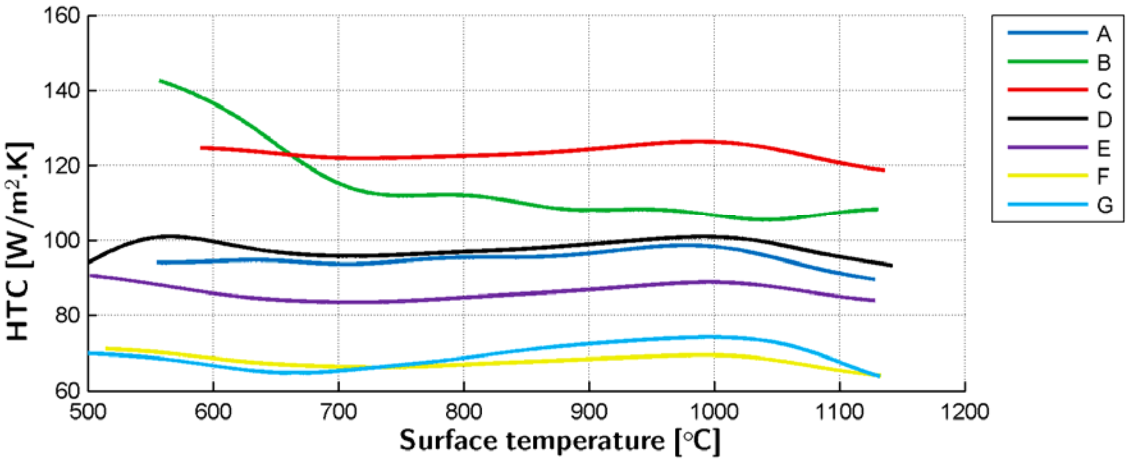
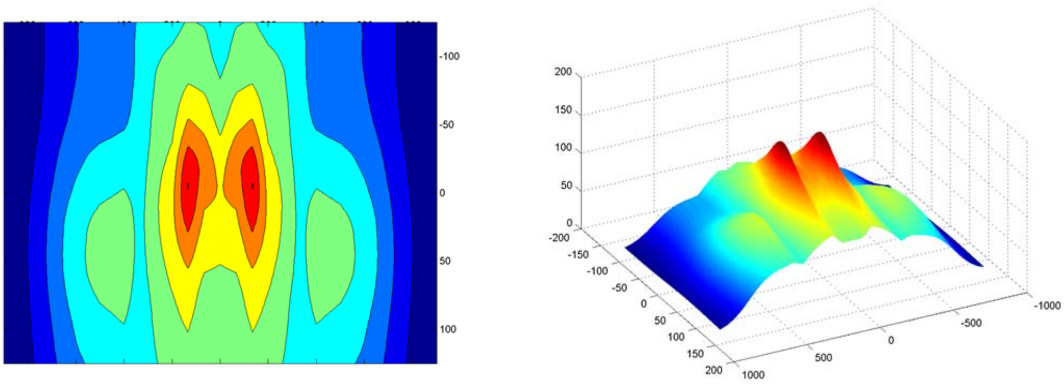


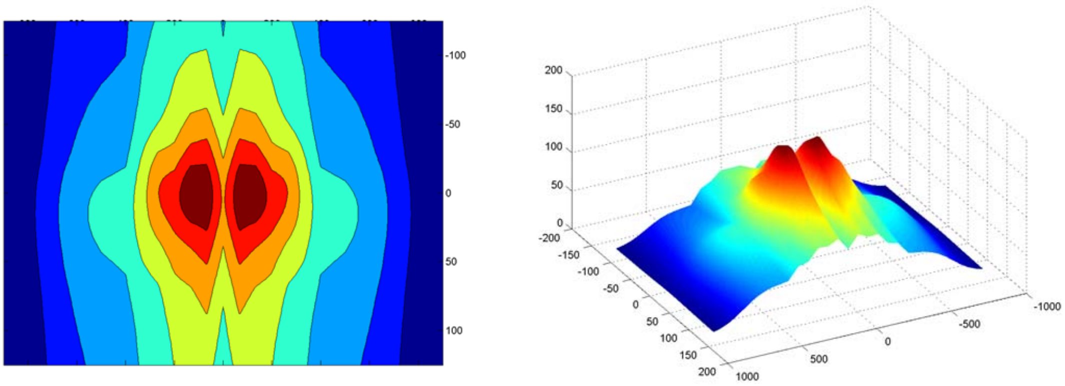
Fig. 4 HTC over temperature

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

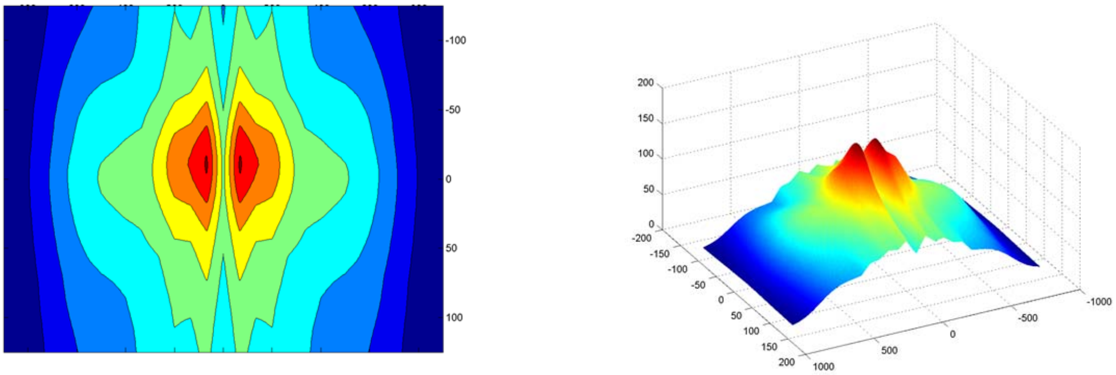
Fig. 5 presents the measured values of the heat transfer coefficients processed by the temperature model software. For nozzle configuration, there is a graph of the 3D graph of the heat transfer coefficient beneath the nozzle. These graphs are plotted for a surface temperature of 800 to 1000 °C.



a) Nozzle 100.638.30.24 water flow 2.2 l/min, air pressure 0.2 MPa



b) Nozzle 100.528.30.24 water flow 2.2 l/min, air pressure 0.2 MPa



c) Nozzle 100.528.30.24 water flow 1.5 l/min, air pressure 0.2 MPa

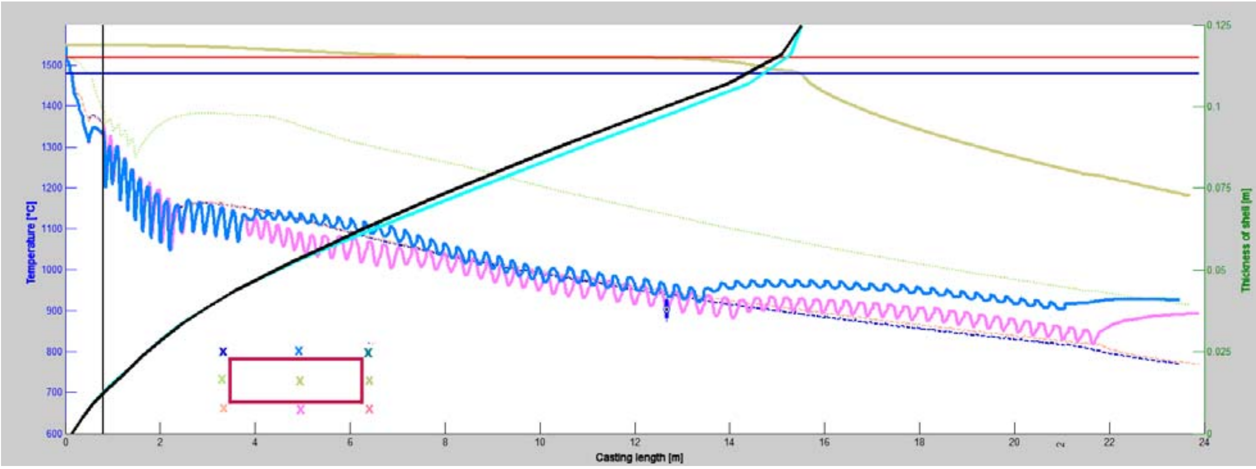
Fig. 5 The heat transfer coefficient for the air mist nozzle Lechler

3. Temperature field

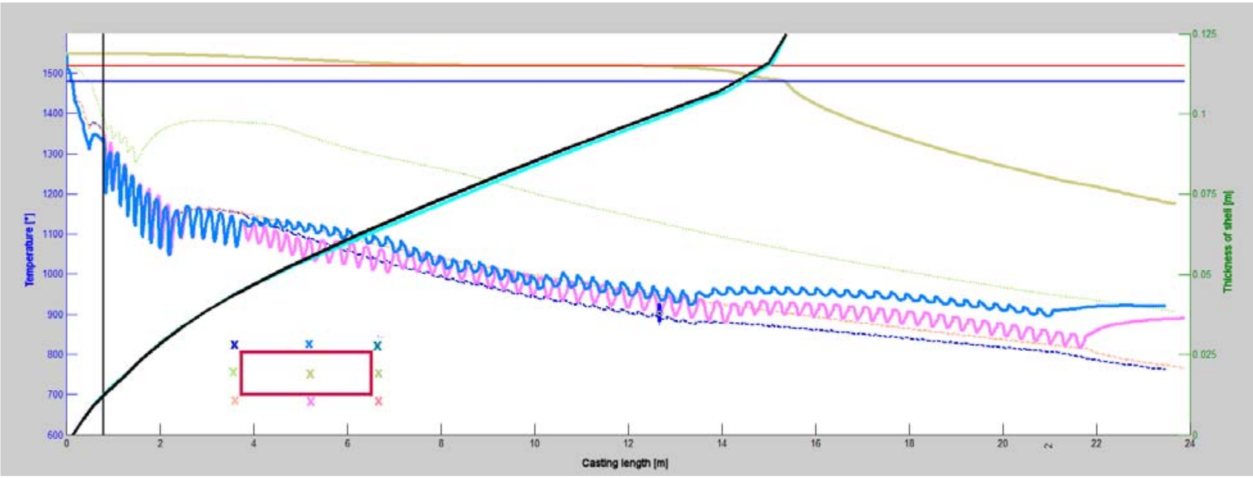
The setting of the secondary cooling and its optimization is a very complicated problem. Therefore, a numerical model of temperature field was used together with the optimization model [4, 5]. The first model is the numerical model of temperature field based on the governing equation of transient heat conduction, also called Fourier-Kirchhoff equation [6].

$$\frac{\partial H}{\partial \tau} + v\frac{\partial H}{\partial z} = \nabla \cdot \left[k_{eff}\left(T\right)\nabla T \right], \tag{1}$$

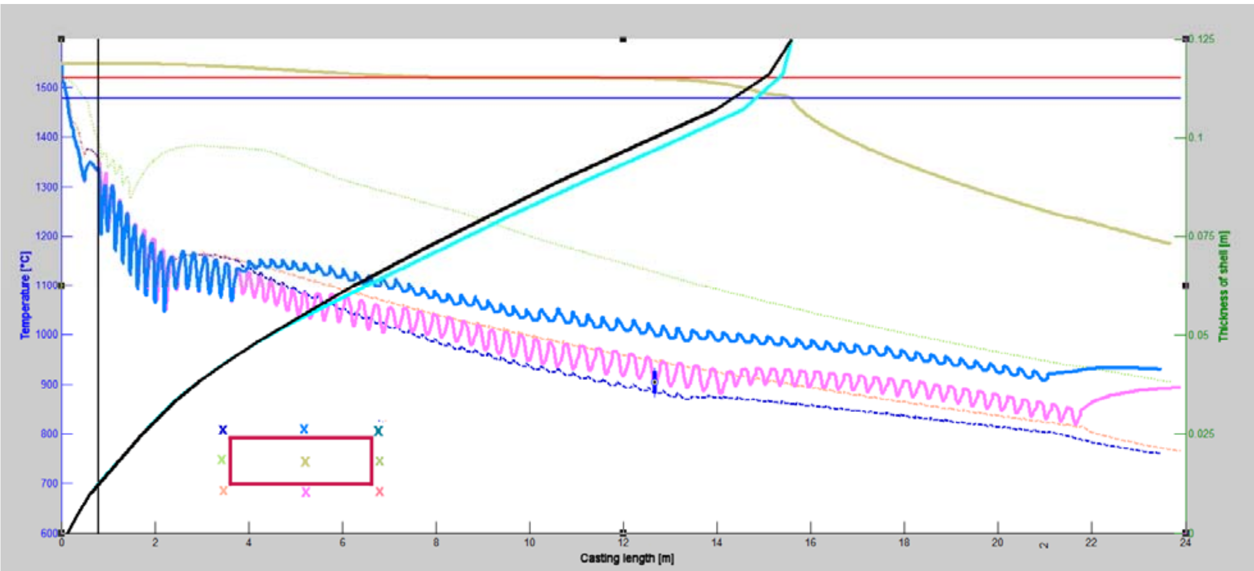
where k_{eff} (W/mK) is the effective thermal conductivity, T (K) is the temperature, H (J/m^3) is the volume enthalpy, τ (s) is time and v (m/s) is the casting speed. This model represents a unique combination of numerical modelling and the large number of experimental measurements. The model is able to predict the temperature distribution in the whole slab, the solid shell thickness and the position of the metallurgical length. Its results are validated by the measurements in the real casting process. In order to speed up the computational time, the model could run in parallel GPU architecture [7].



a) Nozzles 100.638.30.24 water flow per one nozzle 2.2 l/min



b) Nozzles 100.528.30.24 water flow per one nozzle 2.2 l/min



c) Nozzles 100.528.30.24 water flow per one nozzle 1.5 l/min

Fig. 6 Temperature history along caster for different configuration of secondary cooling in zone 6, 8 and 10

The graph in Fig. 6 shows the resultant temperature field for individual cooling curves. This basic set of graphs serves the user in that it is possible to assess which of the cooling curves is optimal for the given cast steel [4]. The Fig. 6a shows the surface temperatures of the slab in the caster using 100.638.30.24 nozzles and current setting secondary cooling to flow 2.2 l/min per nozzle. The following Fig. 6b shows the temperature for the same conditions only in zones 6, 8 and 10 is used 100.528.30.24 nozzle. The last Fig. 6c showing the surface temperature for the water flow 1.5 l/min per 100.528.30.24 nozzle in zones 6, 8 and10. These calculations show that the criteria of the new nozzles increase the surface temperature at the straightening point of the small radius about 100 °C, while at higher flow water rates and the new nozzle can be cooled as intensively as the original nozzle.

4. Statistical processing of data from the on-line model

For each “heat”, the following statistical quantities are calculated for all measured and calculated values: the arithmetic mean, the minimal value, the maximal value and the standard deviation.

The basic statistical quantities are evaluated only from so-called “clean” data – the statistics does not include the transition sections of the first and last heats in the sequence and also the data from any unexpected interruptions in casting. In the evaluation of the statistical data, it is necessary to compare the data for the same slab profile and also for the same class or group of steel. This paper presents the graphs of the statistical quantities for basic slab profile 1530x250 and two one class of carbon steel with an average carbon content of 0.16 % and 0.10 % within a period of 12 months of operation of the caster at EVRAZ VITKOVICE STEEL. The main part of the year in operation original cooling nozzles, the last part of the year are already installed a new smaller cooling nozzles.

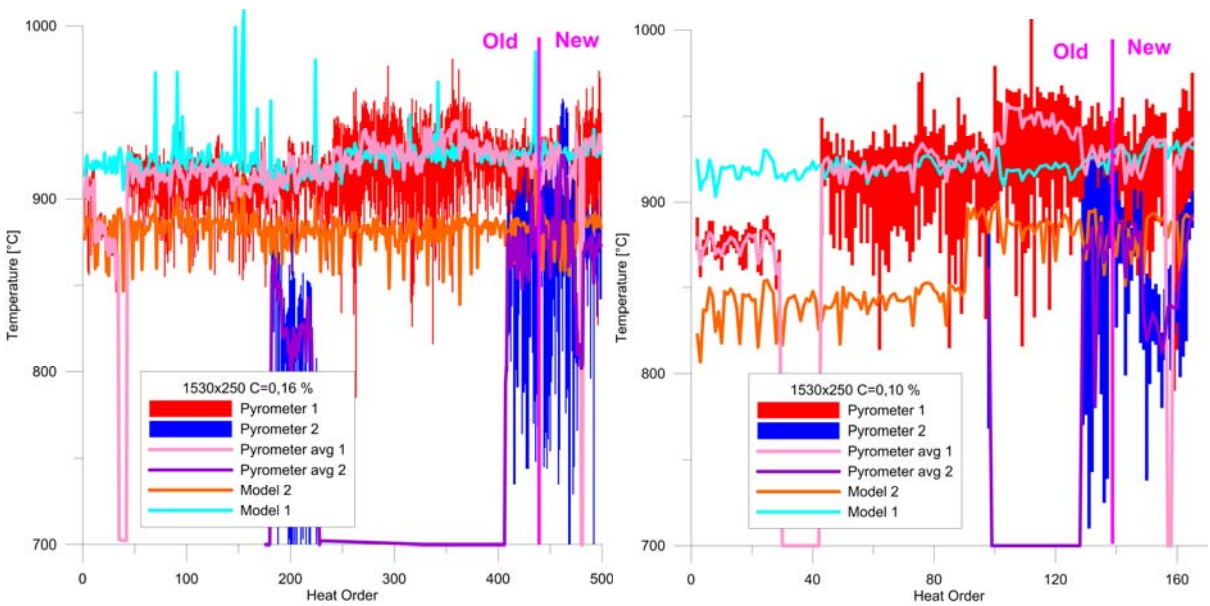


Fig. 7 The measured and calculated temperatures of a 1530×250 mm slab

Fig. 7 compares the average values of the measured surface temperatures in two points with the average calculated temperatures in the same points. The graphs indicate that the measured and calculated values are practically identical in terms of their trends. Comparing the absolute values, it is possible to see that there are long intervals where the deviation is significant and, on the other hand, there are intervals where the values are identical. Furthermore, there are sequences of heats where one pyrometer is out of operation. The conclusion here is that the calculated values of the temperatures are much more reliable and give values that are much more suitable for the prediction system or the secondary-cooling regulation. Another reason why there can be a difference between the measured and calculated temperatures is the state of the secondary cooling. The magenta dividing line is marked heat with replace nozzles.

5. Relationship between casting speed and cooling intensity

The casting process is influenced by many parameters, but only few of them can be controlled in reasonable ranges. For instance, controlling of the casting temperature is not really possible and the safety protocols restrict the water flows through the mould [2]. The typical control parameters are the casting speed and the cooling intensity in the secondary cooling zone.

The optimization goal is to set the casting speed as high as possible and still keep the good quality of cast steel.

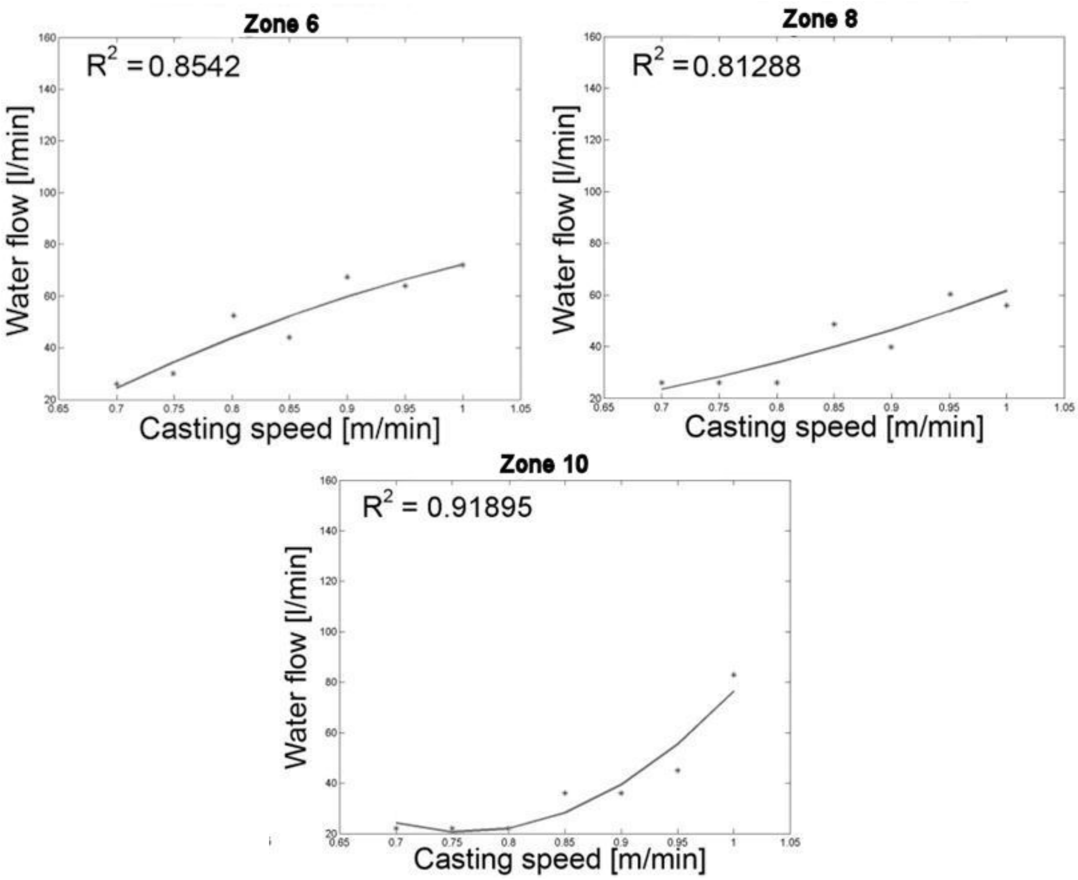


Fig. 8 The optimal cooling curve for cooling zone with new noozle

The search for the optimal relationship between the casting speed and the cooling intensity is simply based on the gradual increase of casting speed (from 0.7 m/min to 1.0 m/min). The algorithm for every value of the casting speed is capable to find a corresponding cooling intensity. From the optimization results the data where the metallurgical length exceeded the given limit (from 14 m to 24 m) and where the maximal error exceeded 100 °C were discarded.

6. Conclusion

The value of the heat transfer coefficient on the surface of the slab, as it enters the secondary-cooling zone, significantly affects the process simulation from the viewpoint of the temperature field, the metallurgical length, and also other technological properties. It therefore enables the prediction of the quality of the slab. In order to be able to simulate this boundary condition within the numerical model as accurately as possible, it is necessary to conduct experimental measurement on each nozzle in the secondary-cooling zone individually. Each nozzle had been measured separately on the hot model, on which the hot surface of the blank, which is cooled by a moving nozzle, can be modelled. The temperatures measured on the surface of the model can be entered into an inverse task to calculate the intensity of spraying, which, in turn, can determine the heat transfer coefficient using a special mathematical method.

The 3D numerical model of the temperature field is used for optimization of the surface temperature of the concast slab. The problem of the optimization of continuous casting process and finding its optimal parameters can be efficiently solved by our algorithm [5]. The results are presented for the 1530x250 mm slabs that are cast in Evraz Vítkovice Steel where the main author’s dynamic 3D solidification model is used to control the production interface. The casting speed is typically set between 0.75 and 0.85 m/min (came up from the practice). The regulation delay was set after many simulations on the value 120 s. Real time model of the temperature field (dynamic solidification model) including optimization model is ready for integration into the Level 2 for example system PIKE automation [9].

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