DRY COOLING SIMULATION OF CONTINUOUS CASTING OF AUSTENITIC STEEL SLABS

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Abstract

Increasing demands on the surface quality of steel slabs together with demands on reduction of water consumption lead to the idea of replacing the secondary cooling zone with water or water-air nozzles by the so-called dry cooling through the supporting rollers. The paper presents the computational study into the dry cooling with the use of the solidification model for continuous steel casting. The simulation is performed for the typical austenitic steel grade S30400. At the moment, the importance of stainless steels grades is increasing again, especially in the automotive industry in design of new types of car bodies as well as in the energetic industry, particularly in case of ultra-critical Rankine cycle. In the paper, a comparison is made for the two cases: a caster with the ordinary secondary cooling zone accommodating water-air nozzles in 13 loops of the secondary cooling zone, and a caster with the dry cooling. In both cases, the radial slab caster casting austenitic steel slabs with the dimensions 1500 mm × 150 mm is considered.

Keywords: Continuous casting, austenitic steel, dry cooling, rollers, secondary cooling

1. INTRODUCTION

The early beginning of continuous casting (CC) of steel is dated to the end of the Second World War and this new method of casting was experiencing the biggest expansion in the sixties and seventies of the twentieth century. Since those days the CC process has been getting great attention as it provides much faster production and higher quality of the concasts than the former ingot casting. The second boom in the CC started with the advanced computer simulations, which provide an opportunity to monitor the casting process and to predict proper boundary and initially conditions to different grades of steel and to assure the most possible steel quality. The focus on high quality products requires production innovations and applications of new approaches supported by technological development.

This paper deals with one of such an innovation in order to obtain a high quality final product without surface cracks. The most frequent surface defects are transversal cracks caused by deep oscillation marks. They result from tensions caused by withdrawal, bulging, bending and straightening of the strand. There is also thermal stress, which results from uneven cooling of the strand shell in the secondary cooling zone [1]. In secondary cooling zone, the heat withdrawal from the slabs is usually made by the spray nozzles. These nozzles use water cooling, which is the main cause of surface cracks. The presented approach pays attention to surface cracks forming due to the water impact oxidation on the surface of the strands. To prevent these surface defects, the secondary cooling is replaced by the so called dry cooling technology. It means that the main heat withdrawal in the secondary cooling zone is made by the supporting internally cooled rollers with the intent to reach comparable results as in the typical nozzle cooling and to provide better quality results of the strand. In some cases, a very low spray cooling flow rate is applied, in order to protect the surrounding machine parts from the strand surface radiation (so called fog cooling) [2].

2. CONSIDERED MATERIAL: AUSTENITIC STAINLESS STEEL

In this work, the aim is focused on the radial slab caster, which is casting the austenitic stainless-steel. Austenitic steels represent over 70% of total stainless steel production. They have typically a higher content of alloying elements, especially chromium, nickel, and manganese, which together with the alloy of iron, forms an austenitic structure. Their peculiarity is that they are not ferromagnetic. Austenitic steels are well weldable, characterized by high toughness but lower strength characteristics. They are poorly machinable and have low a thermal conductivity. Austenitic steels are one of the most widely used corrosion-resistant materials with very good technological properties. Their composition is made up of 18% Cr and 8-12% Ni, which increase the corrosion resistance in severe oxidative-corrosive environments. The most versatile and most widely used stainless steel is the austenitic steel grade S30400 also known as "18/8" for its composition of 18% chromium and 8% nickel. Grade S30400 is readily brake or roll formed into a variety of components for various applications. The composition of the considered steel is presented in **Table 1**.

Table 1 Composition of steel grade S30400

Steel	C	N	Cr	Ni	Mo	Mn	Si	S	P	Cu
Wt %	0.05	0.05	18.3	8.1	0.3	1.8	0.45	0.001	0.03	0.3

3. NUMERICAL MODELS: MATHEMATICAL FORMULATION

The mathematical formulation of heat transfer and solidification to the temperature distribution and solid shell profile prediction is based on the governing equation of transient heat conduction, called Fourier-Kirchhoff equation [3]. In 3D the heat transfer equation reads

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

where k_{eff} is the effective thermal conductivity (W m^{-1} K^{-1}), T is the temperature (K), H is the volume enthalpy (J m^{-3}), t is the time (s), v is the casting speed (m s^{-1}) and z is the direction of casting (m).
To express the relation between the enthalpy and the temperature, we manage to estimate the enthalpy and other termophysical parameters (density, specific heat, thermal conductivity, contraction, etc.) with the use of the solidification analyses package, called IDS [4] (interdendritic solidification software), which is more comfortable and practical to use than expensive and time-consuming experimental investigations.

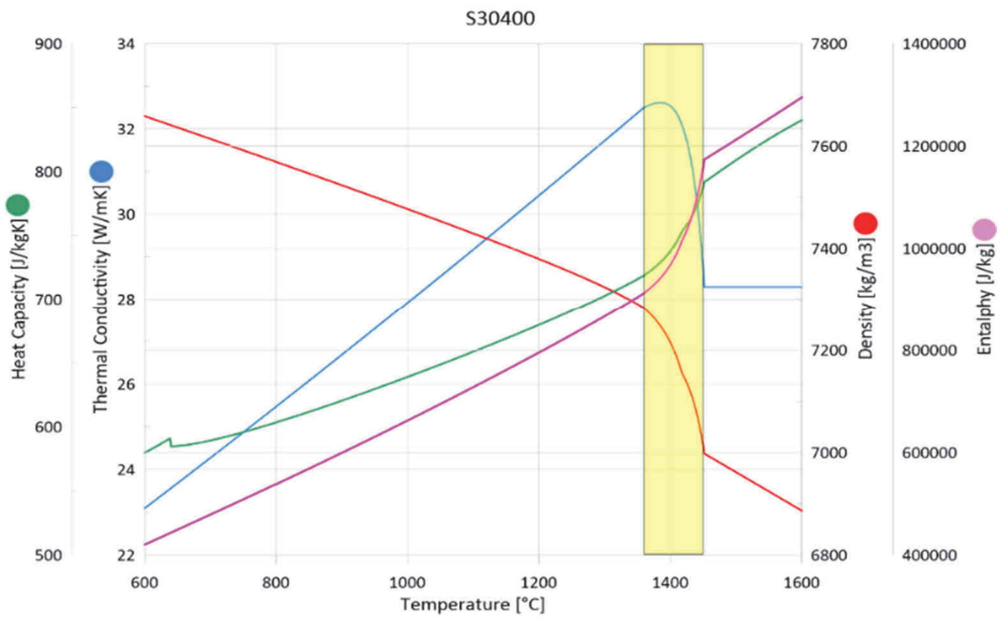

Figure 1 Termophysical parameters of steel grade S30400

The computed parameters of this specific chemical steel composition are displayed in **Figure 1** and they show the temperature-dependences of the total enthalpy, the thermal conductivity, the density, and the specific heat for the austenitic steel grade S30400. The shrinkage of the strand is also embedded in the numerical model and the mesh for the finite difference scheme is non-equidistant.

As for boundary conditions, the determination has to be made properly due to their great influence on computational results. The mathematical formulation of boundary conditions in the CC process has to accompany the heat flux in the mold and under the rollers, forced convection under the nozzles, free convection and radiation. For the typical secondary cooling zone, the boundary conditions are as follows. The heat flux in the roller contact area reads [5]

$$-k\frac{\partial T}{\partial n}=\dot{q}_{rol}=\frac{\pi(l/2)d}{S_{rol}}HTC_{rol}(T_{rol}-T_{amb})+\varepsilon\sigma(T_{rol}^{4}-T_{amb}^{4}), \quad (2)$$

where d is the roller diameter (m); S_{rol} is the roller surface (m^2), and T_{rol} is the roller surface temperature (K). In equation (2) we assume that the heat flux from the strand surface to the rollers is equal to the heat flux from the rollers to the surrounding environment. Heat transfer from the strand is due to forced and natural convection as well as due to radiation in the form

$$-k\frac{\partial T}{\partial n}=HTC(T-T_{water})+\varepsilon\sigma(T^{4}-T_{amb}^{4}), \quad (3)$$

where T_{water} is the cooling water temperature, T_{amb} is the ambient temperature, HTC is the heat transfer coefficient (W m^{-2} K^{-1}), σ is the Stefan-Boltzman constant (W m^{-2} K^{-4}) and ε is the emissivity of slab surface [-]. The appropriate values of HTC for the different types of nozzles were established in Heat transfer and fluid flow laboratory in FME VUT [6].

For the dry cooling the boundary conditions are slightly different. For the part of the process where the heat withdrawal is made by the nozzles (in our work, it means the first 5 meters of the secondary cooling zone), the equation (3) is applied, but in case of heat flux in the roller contact area, we now assume, that the rollers have internal water cooling channels and we can formulate the heat withdrawal under the rollers in terms of energy balance as

$$-k\frac{\partial T}{\partial n}=\dot{q}=\frac{\dot{V}_{water}\rho_{water}c_{water}(T_{out}-T_{in})}{S_{rol}}, \quad (4)$$

where $\dot{V}_{water}$ is the water flow rate through the rollers (L s^{-1}). For the areas where is no roller contact and no water sprayed zone, the heat withdrawal is done mainly in terms of free convection and radiation. The heat transfer coefficient for this part of cooling is then set into the equation (3) and it reads [5]

$$HTC_{nat}=0.84(T_{surf}-T_{amb})^{1/3}. \quad (5)$$

In order to achieve the corresponding results between the water nozzle cooling and the dry cooling, it is necessary to find the optimal heat transfer coefficient (HTC) through the rollers. In case of typical secondary cooling zone, the cooling zone is divided into the segments where nozzles with different cooling properties are used (cooling intensity, impact angle). This means that for the dry cooling, the same HTC should not be used for the same diameter of the roller in order to fulfil the comparable expectations. Another problem occurs at the edges of cooled slabs. While cooling is made by the nozzles, the range of the sprayed does not cover the entire width of the strand and the HTC near edges is lower. Because of that the edges in the dry cooling are experiencing lower temperatures in the transversal cut (top-right, top-left, bottom-right, bottom-left) and are cooled much more due to the even cooling of the whole transverse length.

4. COOLING ROLLERS

In this work the problem is solved with several simplifying assumptions. Due to work of authors [2], the view at the problem about the radiation and roller contact area is not as simple as it could be seen at first glance. Their work is concentrating on the heat flux from the strand to the rollers due to the conduction in the place where the rollers are in contact with the strand and due to the radiation which accounts for a significant heat transfer between the strand and the rollers. The contact area and the contact angle vary with the temperature of the steel, and can be assumed from 4° to 12° degrees in case that the hot shell is very ductile, while the cold steel is experiencing contact less than 4° degrees. This means that if we count with the casting speed, the resulting contact time can vary from 0.05 to 2 seconds depending on roll diameter, casting speed and assumed contact angle. The appropriate construction of the inner cooling channels in the rollers is another issue, for adequate cooling intensities from the roller to the strand due to the roller temperature. It is recommended to assure not too high temperatures at the rollers surface for a long life of the rollers as well as for the temperature of the cooling water inside the channels to prevent the water to start boiling. In the case of radiation, different relationships have to be used than in the typical secondary nozzle cooling. The radiation has a huge impact to temperature rise of rollers. The view angle between the strand and the roller is estimated to be 0°- 120° from one side and the same angle is for the opposite side of it. This means that the 1/3 of total rolling surface is experiencing no heat flux from the strand at the moment and is released to the surroundings. Since only the total heat flux can be measured at the real plant, it is difficult to deduce the respective values of the contact angle and the contact resistance. Especially the influences of the roll diameter, the shell thickness, the contact pressure and the material deformation properties on the contact heat flux are unknown [2].

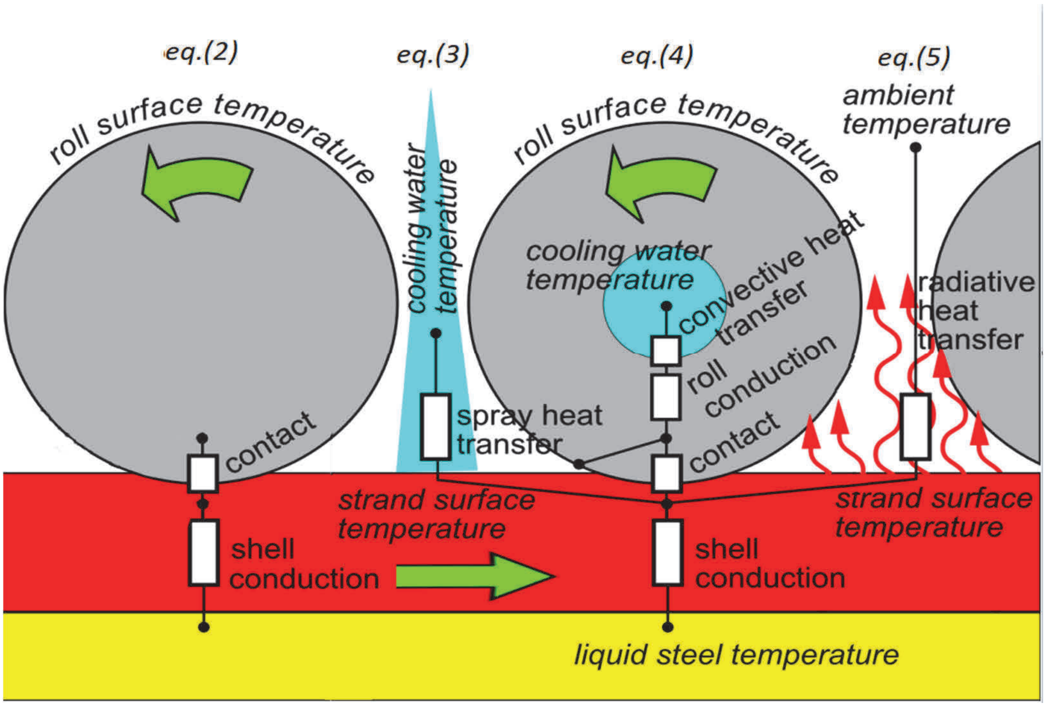

Figure 2 The supporting and cooling rollers [2]

This knowledge is valuable for the further future investigations in order to fulfill the simulation of the real CC process cooled through the method of dry cooling. In our work, the radiation part is simplified as well as the contact angle with the strand and we rather assume to have an average heat fluxes of the area. The problem with the supporting and cooling rollers is depicted in **Figure 2** with appropriate numbers of the equations used in different cases of cooling. The left hand side roller displays the case of supporting roller, where the equation (2) is used. For the internally cooled rollers the temperature resistance is composed from the convective heat transfer in the water channel, conduction through the roller and the strand, as well as the radiation to the surroundings and to the rollers, and for the first five meters the nozzle spray cooling.

5. RESULTS AND DISCUSSION

We created two models, one with a typical secondary cooling and another for the dry cooling with the water nozzle cooling only in the section under the mold (the length of such section is 5 m), together with internally cooled rollers. These rollers are located on the caster within 23 m. The comparison was made for steel caster having the length of 26 m with the dimensions of slab 1500 mm × 150 mm and with the casting speed 1.9 m/min, with 41 computational nodes in x direction and 41 computational nodes in y direction (transverse to the casting direction) and 721 computational nodes in z direction (the casting direction). The results can be seen in **Figure 3**. In case of nozzle secondary cooling (the upper one) the peaks caused by fluctuation of the temperature are not as significant as in the dry cooling. It is mainly due to softer simultaneous cooling by nozzles, as well as by the supporting rollers for which the HTC is not as high and the strand is experiencing cooling more often. Those cooling peaks in dry cooling are the consequence of only roller cooling, which needs much higher HTC to balance the heat withdrawal and the cooling taking place on the smaller surface area.

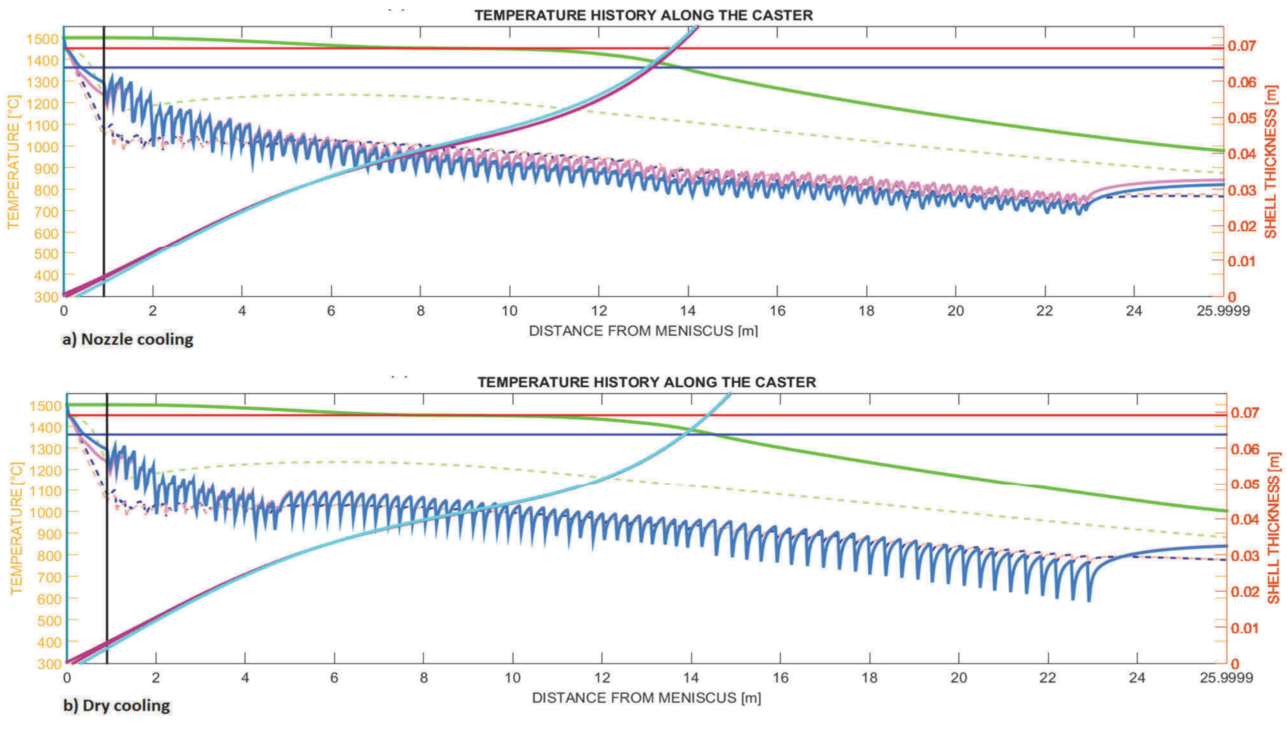

Figure 3 The cooling curves: a) Nozzle cooling, b) Dry cooling

In our model, three different types of cooling rollers are applied (with diameters of 180, 230 and 300 mm) and the appropriate water flow rate through the channels is set from 50 to 400 L/min. This water flow rate is dependent on the channel diameter which also leads to a different assumption about the roller surface temperature. The smaller the distance between the roller channel and the roller surface, the lower the roller surface temperature, which is desired for a long lifetime of the rollers. On the other hand, a higher cooling rate is higher, it leads to lower strand surface temperatures, which is not always desired.

In curved zones of the caster, the cooling water from the sprays can accumulate on the upper surface of the strand, while the droplets tend to bounce off the lower surface. This leads to a difference in the effective heat transfer coefficient between the upper and lower strand surfaces (see the blue and pink curves in **Figure 3**). The final temperature comparison between two models at the end of the caster, reports deviations about 5-10 °C. If we look at **Figure 4**, we can roughly say that the cooling profiles in both longitudinal and transversal cuts behave identically. There are only some little deviations in the metallurgical length and in the longitudinal cut where the solidifying profile behaves more smoothly in case of dry cooling, which is desirable in the CC for the internal quality of strands. This smoother profile is a consequence of even cooling across the width of the slab.

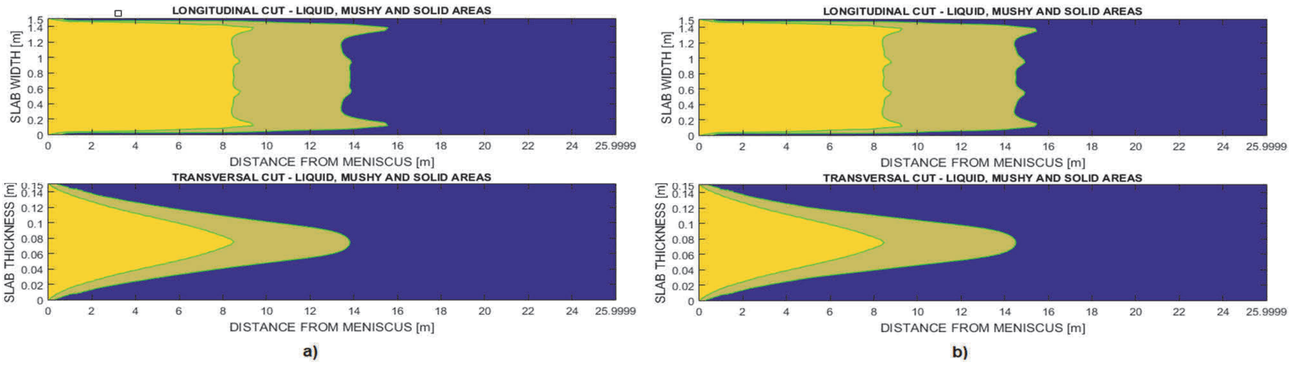

Figure 4 The longitudinal and transversal cuts: a) Nozzle cooling, b) Dry cooling

6. CONCLUSION

This paper deals with the use of dry cooling in the continuous steel casting. The aim of the work was the comparison of this new dry cooling approach with the typical secondary nozzle cooling. The presented results show a quite good congruence between these two approaches. This pilot simulation opens the door to new possibilities in obtaining the free defect strands with no cracks caused by the oxidation of the surface due to the water spray cooling. The other advantage is that the costs for the treatment of the industrial water are reduced because the cooling water flowing through the rollers is used in a closed loop. This can be appreciated particularly in locations with a lack of water. We can conclude that better results can be obtained by a different construction of the cooling channels through the rollers in order to achieve varying HTC as it is in the water spray cooling. But this hypothesis will need much more investigations. Further research will be focused on making the algorithm more precise, especially in the regions where the strand is most sensitive to cracking. Another aim will be to establish the appropriate types of rollers (materials, cooling intensities) for each part of the secondary cooling zone. The focus will also be put to more sophisticated approaches to radiation.

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