1. Introduction

By merging the process of casting and rolling, twin-roll strip casting (TRC) has been proved to be an efficient and energy-saving technology. There are mainly two types of TRC, vertical and horizontal. However, both types of TRC possess their own disadvantages. The fluctuation of molten pool during vertical-type twin roll casting and the complexity of adjustment and maintenance in horizontal twin roll casting remains major problems.

To avoid these problems, our laboratory proposed a top side-pouring twin-roll caster which was composed of unequal-diameter rolls. During the process of the top side-pouring twin-roll casting (TSTRC), only a fraction of a second is taken for the metal melt to transform into solid strip, demanding higher cooling power of rolls compared to the common TRC. Meanwhile the difference of both diameter and structure of two rolls makes it difficult to balance the cooling power of roll surfaces, which leads to a lot of problems during production. Indeed, the casting roll plays an important part in realizing the solidification and formation of metal melt during the TSTRC process. The thermal field of the roll affects the shape of cast strip through its effect on thermal crowning of the roll. Meanwhile the average temperature of roll surface, reflecting its cooling power, affects the surface quality and property of cast strip.

Nevertheless, among researches of the TRC process, most concentrate on the molten pool or the heat transfer of the melt-roll interface, few on the thermal field of roll. Park et al. investigated the influence of the casting speed and the roll diameter on temperature distribution of the roll. And the casting speed was found having a great effect on the roll surface temperature by analysis of the heat flux, which would also be analyzed in this paper. Park et al. studied the thermal crown of the roll in the strip casting process based on the thermal distribution analysis of the roll sleeve. Li et al. analyzed the thermal field of work roll during the hot strip rolling, where the study was focused on the temperature of roll surface and could not reflect the temperature variation with respect to depth in the roll.

However, the variation of interfacial heat transfer coefficient (IHTC) induced by the strip deformation is neglected in all these researches. And nearly no research has poured attention to the thermal field of unequal diameter rolls during the TRC process. Thus in the present work, considering the different stages of the IHTC along the roll/melt interface, a two-dimensional model is developed to investigate the thermal field of the roll and the effects of the rolling speed and the cooling water flux on the cooling power of roll surface during the TSTRC process.

KEY WORDS: top side-pouring; twin-roll casting (TRC); numerical simulation; thermal field; cooling power.
2. Simulation Model and Boundary Conditions

Due to the great complexity of the boundary conditions of the model of the roll in the process of the TRC, it is of particular importance to figure out the model and specify the corresponding boundary conditions, which contains three kinds of heat transfer conditions. With inverse heat-transfer analysis for twin-roll caster, Guthrie et al. confirmed that the heat transfer in axial and circumferential directions of the roll could be ignored compared to the radial heat transfer. Consequently, a two-dimensional model was established and the periodic boundary conditions were set for the roll to investigate its thermal field and the corresponding influencing factors.

The assumptions made in the simulation are as follows:
1. The heat transfer in the axial direction is negligible.
2. The temperature of cooling water is assumed as 20°C.
3. The environmental temperature is assumed as 25°C.

Table 1 shows the main characteristics of the TSTRC caster model and the physical properties of casting roll and casting metal used in the simulation.

The primary temperature of the roll are assumed the same as the environmental temperature and the schematic of the model and boundary conditions are shown in Fig. 1.

Zones of different boundary conditions are shown as follows:

(1) Roll-metal interface zone (A)

The molten metal directly contacts the roll in this zone, where the solidification occurs in few seconds. Due to the extreme complexity of the heat transfer in the roll-metal interface, most researchers simply define the boundary conditions with average IHTC, neglecting the changes of the coefficient along the circumference of the roll.

The heat flux is given by Eq. (1):

$$ q = -k \frac{dT}{dn} = h_f (T - T_r) \quad \text{................. (1)} $$

Where $q$ is the heat flux of the roll-metal interface, $T_r$ the temperature of the molten metal, $h_f$ the heat transfer coefficient of the interface.

Wang studied the inverse heat transfer problem (IHTP) for the TSTRC. The IHTC during the process from melt/roll to strip/roll under different conditions such as superheat, roll gap, slope angle of line joining centers of two rolls and rolling speed is calculated and summarized into 3 stages, chilling, solidification shrinkage and compression. The respective time proportions of these three stages, which remain nearly the same under various roll gap or rolling speed, are averagely 10.67%, 50.54% and 38.79%. According to the work by Wang, when the superheat is 20°C, the roll gap is 1.5 mm and the slope angle of line joining centers of two rolls is $45^\circ$, the values of IHTC at 3 stages are as follows: $h_{A1} = 6.8 \times 10^4$, $h_{A2} = 0.8 \times 10^4$, $h_{A3} = 2.0 \times 10^4$ (W/(m²·°C)).

(2) Strip high/low radiation zone (B1, B2)

The main forms of heat transfer for the roll in this zone are radiation from strip and convection with air. The conditions of radiative heat transfer are as follows:

$$ q = -k \frac{dT}{dn} = h_r (T - T_{ao}) \quad \text{................. (2)} $$

Table 1. Main characteristics of the model and conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting roll Material</td>
<td>5CrMnMo die steel</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>7 830</td>
</tr>
<tr>
<td>Thermal conductivity (W/m·K)</td>
<td>33</td>
</tr>
<tr>
<td>Specific heat capacity (J/kg·K)</td>
<td>460</td>
</tr>
<tr>
<td>Diameter of bottom/upper roll (mm)</td>
<td>400/200</td>
</tr>
<tr>
<td>Roll gap (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Rolling speed (m/s)</td>
<td>$\leq 1.0$</td>
</tr>
<tr>
<td>Slope angle of line joining centers of two rolls ($^\circ$)</td>
<td>45</td>
</tr>
<tr>
<td>Casting metal Material</td>
<td>3wt% Si Steel</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
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</tr>
<tr>
<td>Thermal conductivity (W/m·K)</td>
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</tr>
<tr>
<td>Liquid/Solid specific heat capacity (J/kg·K)</td>
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</tr>
<tr>
<td>Liquidus/Solidus temperature (°C)</td>
<td>1 506/1 480</td>
</tr>
<tr>
<td>Pouring melt temperature (°C)</td>
<td>1 526</td>
</tr>
<tr>
<td>Solidification latent heat (kJ/kg)</td>
<td>248</td>
</tr>
<tr>
<td>Initial thickness of molten metal (mm)</td>
<td>2</td>
</tr>
<tr>
<td>Cooling system Atmosphere</td>
<td>Air</td>
</tr>
<tr>
<td>Number of water holes in bottom/upper roll</td>
<td>50/25</td>
</tr>
<tr>
<td>Diameter of water hole in bottom/upper roll (mm)</td>
<td>8/8</td>
</tr>
<tr>
<td>Distance of water hole from bottom/upper roll surface (mm)</td>
<td>15/20</td>
</tr>
<tr>
<td>Water temperature (°C)</td>
<td>20</td>
</tr>
<tr>
<td>Cooling water flux rate (m³/h)</td>
<td>2–9</td>
</tr>
</tbody>
</table>

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\[ h_{ro} = \varepsilon \sigma (T^2 + T_{oo}^2) (T + T_{ro}) \] ........................ (3)

Where \( \varepsilon \) is the emissivity of roll surface (0.21), \( \sigma \) the Stefan-Boltzmann constant (5.67 \times 10^{-8} \text{ W/(m}^2\cdot\text{K}^4))\), \( h_{ro} \) the heat transfer coefficient of roll-strip interface, \( T_{oo} \) the temperature of strip surface. Different values are set for zones of B1 and B2.

(3) Air convection zone (C)
Both of convective and radiative heat transfer between the roll and air exist in this zone.

\[ q = -k \frac{\partial T}{\partial n} = h_{air} (T - T_{air}) + \varepsilon \sigma (T^4 - T_{air}^4) \] ........................ (4)

Where \( \varepsilon \) is the emissivity of roll surface (0.21), \( \sigma \) the Stefan-Boltzmann constant (5.67 \times 10^{-8} \text{ W/(m}^2\cdot\text{K}^4))\), \( h_{air} \) the coefficient of air natural convective heat transfer (10 \text{ W/(m}^2\cdot\text{K}))\), \( T_{air} \) the temperature of air.

(4) Molten pool radiation zone (D)
For roll surface in this zone, the main forms of heat transfer are radiation from molten pool and convection with air. The conditions of radiative heat transfer are as follows:

\[ q = -k \frac{\partial T}{\partial n} = h_{ir} (T - T_{ir}) \] ........................ (5)

\[ h_{ir} = \varepsilon \sigma (T^2 + T_{ir}^2) (T + T_{ir}) \] ........................ (6)

Where \( \varepsilon \) is the emissivity of roll surface (0.21), \( \sigma \) the Stefan-Boltzmann constant (5.67 \times 10^{-8} \text{ W/(m}^2\cdot\text{K}^4))\), \( h_{ir} \) the heat transfer coefficient of roll-melt interface, \( T_{ir} \) the temperature of melt surface.

(5) Water forced convection zone (E)
The primary form of heat transfer between the roll and cooling water is forced convection.

\[ q = -k \frac{\partial T}{\partial n} = h_{w} (T - T_{w}) \] ........................ (7)

Where \( T_{w} \) the temperature of cooling water (20°C), \( h_{w} \) the coefficient of water forced convection heat transfer (1 000–15 000 \text{ W/(m}^2\cdot\text{K}))\).

Based on the calculation of Reynolds number, the cooling water in the roll is defined as turbulent flow, for which the IHTC can be calculated by Gnielinski formula as follows:

\[ N_{uf} = \frac{hd}{k} = \left( \frac{f}{8} \right) (Re - 1 000) Pr_1 \left[ 1 + \left( \frac{d}{T} \right)^{2/3} \right] C_l \] ........................ (8)

Where \( N_{uf} \) is the Nusselt number, \( Pr_1 \) the Prandtl number, \( \mu \) the dynamic viscosity, \( C_p \) the specific heat, \( k \) the thermal conductivity, \( h \) the convection heat transfer coefficient, \( Pr_w \) the Prandtl number of water under wall temperature, \( C_l \) the coefficient which is calculated by \( C_l = (Pr_1/Pr_w)^{0.11} \) for liquid and \( C_l = (Pr_1/Pr_w)^{0.45} \) for gas, respectively.

3. Results and Discussion
3.1. Thermal Field of Bottom Roll
3.1.1. Variation of Heat Flux and Temperature
Heat flux is the rate of heat energy that passes through a given surface per unit area and per unit time, measured in \text{ W/m}^2 and given by:

\[ q = h \cdot \Delta T \] ........................ (9)

Where \( h \) the heat transfer coefficient, \( \Delta T \) the temperature difference of roll/melt interfaces.

The heat flux curves appeared single-peak or double-peak in the previous researches of TRC process. Tavares et al. from Canada investigated the heat flux curves of roll-melt interface and the relationship between the curve shape and rolling speed in the TRC process of low carbon steel. When the rolling speed was low (4 m/min), the heat flux curves appeared single-peak. After reaching the top, the heat flux decreased dramatically for the following reasons. The first was the decrease of the metallostatic pressure caused by the thicker and stronger solidified shell close to the roll nip. The second was the reduction of physical contact triggered by solidification shrinkage. Besides, when the rolling speed was high (7–8 m/min), the second peak of heat flux curves was observed, which was attributed to the latent heat of solidification.

Figure 2 is the schematic of the TSTRC process in the present work. And Fig. 3 shows the variation of heat flux and temperature along the circumferential bottom roll surface after 50 revolutions, where the 0° position of calculation start is shown in Fig. 1. For curves of heat flux, the first peak is triggered by sudden contact between the roll and melt, which dramatically increases the heat transfer on the roll surface. As illustrated in Fig. 3, the continuous little fluctuation of heat flux after the first peak reflects the comprehensive influence of releasing latent heat and various metallostatic pressure, corresponding to the procedure from the solidification front to the solidification end in Fig. 2. During this procedure, as a result of the various height of the melt along the roll surface, the metallostatic pressure over the solidified shell gradually decreases with thicker solid shell and then increases when close to the upper roll. Higher metallostatic pressure leads to higher contact pressure and thinner gas film between roll and metal. And according to the work by Mizoguchi et al., the heat transfer coefficient on the metal surface decreases with the increase of the gas film thickness between roll and metal. Consequently,
the variation of the metallostatic pressure add to the same changing trend of the heat flux, which is believed to be reflected in the second and third stages of the IHTC. Similar to the previous work of Tavares et al., the second peak of the heat flux was observed in the simulation results, lower and wider than the first peak. According to the schematic of the TSTRC process, the second peak can be ascribed to the rolling pressure, corresponding to the location of solidification end close to the roll nip. According to the research of Wang, the IHTC was observed increasing with the rise of contact pressure. Under a certain condition, the IHTC increased from \(1.6 \times 10^4\) W/(m\(^2\).°C) to \(1.8 \times 10^4\) W/(m\(^2\).°C) when the contact pressure increases from 7 kN to 9 kN. The rolling pressure leads to dramatic increase of the contact pressure after the solidification end. Correspondingly, the IHTC used in the simulation rises from \(0.8 \times 10^4\) W/(m\(^2\).°C) to \(2.0 \times 10^4\) W/(m\(^2\).°C). Thus as has been said, according to the curve shape of heat flux, the latent heat of solidification is believed to be associated with the continuous fluctuation after the first peak, meanwhile the rolling pressure is believed to cause the second peak of the heat flux.

As Fig. 3 illustrates, the curve shape of the temperature is partly similar to the heat flux. Equation (9) reveals the correlation between the heat flux and the temperature difference of roll/melt interfaces. When the temperature of the melt surface and the IHTC are obtained, the temperature of roll surface can be derived from the heat flux. This may explain the similarity between the curves of temperature and heat flux.

Compared to the experiments of Tavares et al. in the TRC process of low carbon steel, the similar relationship between the rolling speed and heat flux curves of roll-melt interfaces is found in the present work. Figure 4 shows the relationship between two peaks of heat flux curves with dif-
different rolling speed. When the rolling speed is high, the heat flux curves appears obvious double peak. Furthermore, with the rolling speed decreasing, the ratio of the second peak to the first one decreases, meanwhile the curve shape gradually approaches single peak. According to Eq. (9), the variation of the heat flux with the rolling speed primarily depends on the temperature difference of roll/melt interfaces for the IHTC is constant. In other words, the heat flux is positively associated with the temperature difference. So when the rolling speed is slower, the longer contact time between the melt and roll surface will make the temperature difference along the interface smaller and more uniform, which may explain the changes of two peaks of heat flux with the rolling speed.

3.1.2. Temperature Distribution of Bottom Roll

Figure 5 shows the temperature variation of point 1–3 in the bottom roll during 50 revolutions. As illustrated in Fig. 2, the monitoring P1, P2 and P3, which locates in the perpendicular bisector of adjacent water hole centers, are 0 mm, 8 mm, and 13 mm away from roll surface, respectively. For points at different distances from roll surface, the total changing trend of the temperature remains the same. The overall temperature of each revolution increases quickly at first and then gradually approaches the top, with periodic variation during the whole procedure. Consequently, the steady state can be established quickly and easily, with the temperature of P1 ranging from 632°C to 1 076°C, P2 from 492°C to 504°C, and P3 from 365°C to 366°C.

Figure 6, the polar diagram of temperature variation of P1 at bottom roll surface, the X-coordinate of which corresponds to angular, can obviously reflect the periodic temperature variation. As seen, the temperature curves appear double-peak for each revolution, where the second peak is lower and wider than the first one. Corresponding to the rotation of the roll, the point at roll surface reaches the melt region at OA and leaves the roll nip at OB. Accordingly, the first peak is due to the dramatic increase of the temperature of roll surface when suddenly contacting the melt region, meanwhile the second peak is primarily ascribed to the influence of rolling pressure close to the roll nip, as mentioned earlier.

Figure 7 shows the temperature variation curves in a revolution at different distances from roll surface after 50 rotations of bottom roll when its temperature field is steady. First it is observed double-peak for the temperature curve of roll surface. And with distances from roll surface increasing, the fluctuation range of curves becomes smaller, meanwhile...
the curve shape of double peak gradually transforms to the single peak, the abscissa value of which delays as well. When the distance from roll surface is more than 2 mm, only curves of single peak can be observed. Among curves at different distances from roll surface, the biggest fluctuation is observed in the curve at roll surface. Accordingly, the thermal shock, which causes tension in a material, is mostly undertaken by the layer close to roll surface and weakens abruptly with the distance from roll surface increasing.

Compared with conventional continuous casting, no mold flux is used to prevent the mold/melt heat transfer in the TRC process, making its melt cooling rate and interfacial heat flux much higher. Thus in the TRC process, the solidification of the melt is completed during a fraction of a second, meanwhile the roll undertakes large temperature variation during rotation. On the one hand, the structure of solidified metal is greatly influenced by the cooling rate. According to the research of Mizukami,\(^{12}\) the primary arm spacing and surface grain size of rapidly solidified steel decreases with increasing cooling rate, which is in the range of 1 000–30 000°C/s. On the other hand, the thermal stress and working life of roll are closely associated with the temperature changing rate in the roll which is investigated below.

Figure 8 presents the maximum of temperature changing rate and standard deviation of temperature for different locations under bottom roll surface in a revolution. The standard deviation, reflecting the fluctuation range of the temperature, is in power-law relationship with the distance from roll surface due to their linear relationship in the coordinate of Fig. 8. When the distance from roll surface is more than 6 mm, the standard deviation is less than 10°C. The maximum, reflecting the degree of the temperature variation at certain distance from roll surface, changes obviously at the abscissas of 3 m, as illustrated in Fig. 8. In conclusion, the maximum of temperature changing rate is not less than 270°C/s for distance less than 3 mm, and up to 10 638°C/s for roll surface. However, for distances more than 6 mm, the temperature changing rate drops abruptly to the value less than 50°C/s.

Consequently, the thermal shock was mostly concentrated in the 6 mm layer under roll surface, especially in 3 mm layer. The simulation results of temperature distribution and its changing rate in the roll are helpful for estimating the roll life and predicting the thermal crowning of roll, as well as the shape of cast strip.

3.2. Factors Influencing the Cooling Power of Roll Surface

In the process of TSTRC, only a fraction of a second is taken for the metal melt to transform into the solid strip. Thus the cooling power of roll surface, which influences the cooling rate of melt and determines the solidification end
The molten metal is constantly cooled by the rotating roll surface during the roll casting process. Thus, the lower temperature the roll surface has, the more easily it can take away the heat from the molten melt, and the stronger its cooling power is. So as to quantify and measure the cooling power of roll surface, the average temperature of roll surface is used in the following analysis.

To bring the cooling power up to the required standard, both the size and distribution of water holes should be taken into consideration in the design of roll structure. However, in practical production, only parameters of the cooling water flux and the rolling speed can be adjust to control the cooling power of roll surface, which is analyzed in further detail below.

3.2.1. Influence of Rolling Speed

In the process of twin roll casting, the variation of the rolling speed can change the contact time and the heat transfer between the roll and melt, thus influencing the temperature of roll surface.

Figure 9 illustrates the circumferential temperature of bottom roll surface with respect to different rolling speed when the temperature field in roll is steady, where the $0^\circ$ position of calculation start is shown in Fig. 1. With the roll surface divided into high-temperature and low-temperature zones according to whether the zone is in contact with the melt, then as seen in Fig. 9, the high-temperature zone increases while the low-temperature zone decreases with the increasing rolling speed.

More specifically, Fig. 10 shows the relationships of average, maximum and nip’s temperature of roll surface with the rolling speed. In Fig. 10, when the rolling speed rises in the range of 0.3–1.0 m/s, the average temperature is observed increasing parabolically, while the maximum and nip’s temperature declines in approximate straight line.

With the rolling speed increasing, more heat is taken away from the molten pool by the roll per unit time. So increasing the rolling speed can amplify the efficiency of heat absorption for the roll, meanwhile the average temperature of roll surface is higher, compliant with the results in Fig. 10(a). In summary, the cooling power of roll surface, due to its negative correlation with the average temperature, decreases with the increasing rolling speed.

Japanese researchers Hirano et al. calculated the heat transfer coefficient by measuring temperature of outer roll and studied its influence on roll and strip in the TRC process of 304 stainless steel. The decreasing tendency of maximum temperature of roll surface with increasing rolling speed was observed and there were two reasons proposed to explain this phenomenon. One is the reduction of contact time between melt and roll with the rolling speed increasing, the other is the decrease of heat transfer coefficient. In the present work, as seen in Fig. 10(b), the same phenomenon is observed in the results of simulation. However, the heat transfer coefficients used in the simulation are constants, demonstrating that the former reason is more likely to be responsible for this phenomenon.

Park et al. investigated the relationship between the rolling speed and temperature distribution of roll in the TRC process, finding that the temperature of roll surface at roll nip increased when the rolling speed rose from 40 mpm to 120 mpm. On the contrary, as illustrated in Fig. 10(c), the temperature at nip decreases with the increasing rolling speed. This is because during the TSTRC process, the decrease of heat flux that the roll receives from the pouring point to the roll nip is more effective than the reduction of cooling time in the increase of the roll temperature.

From the perspective of the roll, higher rolling speed brings higher efficiency of removing heat from the melt, which may mean stronger cooling power. Nevertheless, the true cooling power should be considered in the perspec-
tive of the melt instead of the roll. During the process of TSTRC, the melt is nearly relatively static to the roll surface, resulting in the decrease of its contact time with the roll with the increase of the rolling speed, thereby reducing the corresponding heat taken away from a unit mass of the metal melt.

Consequently, higher rolling speed leads to higher temperature and lower cooling power of roll surface. Furthermore, not only the cooling power of roll surface decreases with the increasing rolling speed, its decreasing rate reduced as well.

### 3.2.2. Influence of Cooling Water Flux

Figure 11 presents the steady circumferential temperature of bottom roll surface with respect to cooling water flux, where the 0° position of calculation start is shown in Fig. 1. As illustrated in Fig. 11, when the cooling water flux rises in the range of 2–9 m³/h, the whole temperature curve of roll surface moves down, with the moving rate declines as well.

**Figure 12** shows the relationship between the cooling water flux and the average circumferential temperature of bottom roll surface when its temperature field is steady. The average temperature of roll surface represents the cooling power of roll surface for the lower temperature of roll surface meant higher ability of absorbing heat from molten pool. As seen in Fig. 12, with the flux of cooling water increasing, the average temperature of roll surface decreases while its decreasing rate declines as well. This indicates that the cooling water flux should be more effective in affecting the cooling power of roll surface when the water flux is lower, especially when less than 6 m³/h.

As discussed above, the influence of the rolling speed and the cooling water flux on the cooling power of roll surface was evaluated by analyzing their relationships with
the average temperature of roll surface. In conclusion, the rolling speed and the cooling water flux are believed having positive and negative correlation with average temperature of roll surface, respectively. Then by comparison of average temperature ranges between two groups of simulation results, which are approximately 35°C and 200°C respectively, the cooling water flux is the more important factor in influencing the cooling power of roll surface.

In the simulation test of hot rolling of stainless steel carried by Jin et al., the sticking phenomenon occurred more severely when the test temperature, measured above the roll surface, increased in a range below about 900°C. While in the previous experiments of the TSTRC, the metal strip was also observed easily stuck to the upper roll, which was believed primarily due to the lack of the cooling power of roll surface. More specifically, the lower cooling power leads to higher average temperature of upper roll surface and corresponding strip surface, thereby increasing the sump depth and the friction coefficient on strip surface and finally resulting in the sticking phenomenon. Meanwhile, the sticking to the upper roll is believed essentially attributed to the difference between the cooling power of upper and bottom rolls, which will be explained in further detail below.

As mentioned above, the cooling power of roll surface can be controlled by means of changing the cooling water flux and the rolling speed. However, due to the same linear rolling speed of two rolls in the TSTRC, only the cooling water flux remains available to balance the cooling power of two rolls.

Figure 13 illustrates average temperature of two roll surfaces with different cooling water flux. As showed in Fig. 13, the average roll surface temperature of two rolls is nearly the same when the cooling water flux is 4 m³/h for the upper roll and 6 m³/h for the bottom roll respectively. However, when the cooling water flux of the upper roll increases to 6 m³/h, the flux of the bottom roll need to grow up to 9 m³/h to maintain the balance of cooling power of two rolls. Besides, the increase of the cooling water flux is less effective in reducing the average temperature of roll surface when the water flux of the bottom roll is more than 6 m³/h. Accordingly, the suitable cooling water flux are 4 m³/h and 6 m³/h for the upper and bottom roll respectively within the range of casting roll conditions that were studied in this paper.

When the cooling water flux varies from 2 m³/h to 8 m³/h, the variation of average roll surface temperature per revolution of two rolls is compared in Fig. 14. The average temperature of roll surface under various cooling water flux remains nearly the same from 0 s to 11 s for both two rolls. So as to reduce the temperature difference in the later stage, as illustrated in Fig. 14, the proper cooling water flux will be 6 m³/h for the bottom roll and 4 m³/h for the upper roll, or 8 m³/h for the bottom roll and 6 m³/h for the upper roll. The temperature difference curves under these two groups of conditions are also illustrated below, where the values reach the peak of about 110°C after 5 revolutions of the bottom roll and then gradually falls to nearly zero. With lower cooling water flux, the temperature difference under the first group of conditions is similar to or even less than that under the second group of conditions. This strengthens the point that the suitable cooling water flux is 4 m³/h and 6 m³/h for the upper and bottom roll respectively, within the range of studied conditions. However, the temperature difference before 11 s is independent with the cooling conditions, up to about 110°C. This can be an evidence of the phenomenon that the strip is more easily stuck to the roll at the earlier stage in the TSTRC process, while the similar behavior was observed in the initial process of hot rolling according to the research of Jin et al. and Son et al. The temperature difference of two rolls leads to the corresponding temperature difference between the two sides of the strip surfaces, where the temperature of the upper side is lower than the bottom one. This can add to the bending trend of the strip toward the upper roll and increase their contact region, considering the thermal expansion of the metal. That’s why the metal strip, as mentioned above, was observed easily stuck to the upper roll, especially in the initial stage where a great temperature difference existed. Meanwhile the increase of average temperature of the upper roll surface, much less than the temperature difference of two rolls in this stage, does not change the bending trend of the metal strip but can increase the sump depth and the friction coefficient on
contacting strip surface, thereby adding the possibility of the sticking phenomenon to some extent.

4. Conclusions

It should be the first time that the simulation of thermal field of unequal diameter rolls during the TRC process was discussed. Using a two-dimensional model, the thermal field of the roll and the effects of the rolling speed and the cooling water flux on the cooling power of roll surface were investigated during the TSTRC process.

Considering the variation of the IHTC along the roll/melt interface, the heat flux and temperature curves of roll surface were both observed to be double peak, where the second peak was believed essentially attributed to the rolling pressure. And the relationship between the curve shape and the rolling speed obtained in the simulation results partly confirmed the previous work of Tavares et al.\(^{10}\) in the TRC process.

The rolling speed and the cooling water flux were found having negative and positive correlation with the cooling power of roll surface, respectively. Furthermore, the cooling water flux affected the cooling power more than the rolling speed did. And as to balance the cooling power of two roll surfaces, the suitable cooling water flux obtained in the simulation was 4 m\(^3\)/h and 6 m\(^3\)/h for the upper and bottom rolls respectively within the range of casting roll conditions that were studied in this paper. The simulation results can help provide effective data for solving the problem of the sticking of the strip to the roll. Besides, the roll material, both the size and distribution of water holes are believed to make great difference in the cooling power of roll surface. And these factors will be investigated in the future and then taken into consideration in the structure design of our next generation of the twin-roll caster.

In conclusion, the work of this paper should help realize the heat transfer of the roll/melt interface, clarify effects of the rolling speed and the cooling water flux on the cooling power of roll surface, and improve the design of the cooling system. From a broader perspective, effective simulation results are provided for estimating the roll life and predicting the shape of cast strip through effect of thermal field of the roll on its thermal crowning.

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