Mould Heat Transfer in the Continuous Casting of Round Billet

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Mould heat transfer behaviors during the continuous casting of round billets are elucidated in this paper. Round copper moulds were instrumented with 72 thermocouples and mould temperature together with heat flux were monitored simultaneously with mould powder lubrication during continuous casting of a diameter 178 mm round billets. The profiles of the temperature and heat flux were analyzed based on the longitudinal and circumferential monitoring data under different installation status of moulds. The influences of steel carbon content, casting speed, and mould oscillation frequency on heat transfer have been discussed especially at position 70–110 mm below the meniscus where the heat transfer was the highest and most sensitive to operational parameters. Eventually, the correlation coefficient, defined as the correlation of local heat flux and temperature (CCHT) in the hot face of mould around the mould circumference at the same mould height, has proved to be a good characteristic parameter for analyzing the influence of scale on abnormal heat transfer in quantity.

KEY WORDS: heat transfer; CCHT; mould; round billets; continuous casting.

1. Introduction

The objective of conducting an instrumented mould trial is to investigate the behaviors of the mould and billet, and determine the optimal mould design to minimize defects and maximize productivity. Surface defects, such as longitudinal or transverse cracks, star cracks, longitudinal off-corner depressions and deep oscillation marks, could have been observed and analyzed with the help of thermocouples buried in the mould wall. Brimacombe and co-workers have devoted to inspecting slabs/billets mould behaviors with oil or powder lubrication for several decades. Meanwhile, many online monitoring systems have been set up, giving rise to valuable information that has allowed the study of frictional force and some transient phenomena that appear during the continuous casting operation. Yao and Fang have developed a mould/strand friction monitoring system that can be used for predicting abnormal friction and breakout. The system could measure power signal and the total mould/strand frictional force, however, could not supply thermal information of continuous casting process. Alvarez de Toledo et al. inspected the mould cooling water temperature increase using moulds instrumented with 24 thermocouples in the billets. The heat flux, which was calculated from temperature measurements of the thermocouple pair at each position, has been detected to drift for mould powder basicity larger than 0.8. Pinheiro et al. have analyzed thermal behaviors of billets under various operational parameters condition such as oscillation frequency, mould cooling water velocity and steel composition, an inverse heat conduction model was also developed to calculate mould heat flux based on measured temperatures. The mould heat transfer and defect information obtained for mould flux lubrication have been compared with those for oil lubrication.

Unfortunately, there have been few amounts of work done in round billets compared with slabs and billets. Yao et al. have been researching the thermo-mechanical behaviors in the mould for small round billet continuous casting for several years. In their previous works, distributions of temperature and heat flux around mould perimeter have been analyzed, and a multi-dimensional, coupled, inverse problem model was developed from the measured data of mould temperature by thermocouples embedded in various transverse and longitudinal sections for a round billet in normal production. The researching results can be provided as a basis for real-time monitoring. However, the variation and non-uniformity of temperature and heat flux have not been compared between normal and abnormal production in quantity, and the influences of steel grade, casting speed, mould oscillation frequency and mould installation on the heat transfer in the mould were not discussed in detail.

In the present work, a system monitoring mould temperature and heat flux online in continuous casting of small round billets is described, some transient phenomena that took place in the mould are analyzed, with special attention to heat flux under different installation of moulds. The influences of some casting parameters on mould heat transfer have been investigated. The local temperature and heat flux responses are also studied in quantity under abnormal heat transfer conditions such as scale and the correlation coeffi-
cient of the heat flux and temperature (CCHT) in the hot face of mould is utilized to appraise the influence of scale on unbalanced heat transfer in quantity. The measured data and subsequent analysis are to establish the relationship between the heat transfer and the casting operational parameters and then to apply the findings to the industrial process.

2. Industrial Trial

The procedure for instrumentation of round billet moulds and measurement of mould wall temperature and heat flux during casting was established and has been discussed in detail elsewhere.\textsuperscript{11,12} In this particular trial, type K (NiCr–NiSi) thermocouples were employed to measure the mould wall temperature. Thereby heat flux can be obtained simultaneously. The thermocouples were held in mechanical contact with the mould with purity copper plugs. From the top of mould, there were 95, 155, 245, 365, 515 and 650 mm (expressed with 1L, 2L, ..., 6L) where six rows of thermocouples were embedded in the mould at six transverse faces. To investigate the variability and non-uniformity of the transient phenomena around the mould circumference, in six longitudinal faces, with an angle of 60° between any two of them, six arrays (denoted by 1, 2, ..., 6, respectively; 0° stands for inner arc of the mould, is denoted as 1, and 300° as 6) of measured points were also set to specify the uniformity, and there were 36 monitoring points with 72 thermocouples in all. Each spot had two thermocouples, the distance between them was 3.5 mm as shown in Fig. 1. The thermocouples close to mould hot face are denoted with “H” and those close to cold face are denoted with “C” to describe the temperature. For example, 3L1H denotes for the temperature of thermocouple in the hot face at the third layer (245 mm from mould top) at degree 0 (inner-arc), and 4L4C denotes for the temperature of thermocouple in the cold face at the fourth layer (365 mm from mould top) at degree 180 (outer-arc). Additionally, the arrays attached the number “1, 2, ..., 6” are used to describe the heat flux. For instance, 2L2 denotes for the heat flux at the second layer (155 mm from mould top) at degree 60 from degree 0 (inner-arc), and 6L6 denotes for the heat flux at the sixth layer (650 mm from mould top) at degree 300 from degree 0 (inner-arc). The data collection occurred at 2 Hz and included other important parameters, such as mould cooling water temperature, casting speed, metal level and mould oscillation characteristics.

The plant trial industrial was carried out with a curved billet casting machine with a radius of 9.9 m, which had a six strand. The mould on which measurement were conducted was tubular and made of copper, and had a double taper and a diameter 181 mm. The mould walls were 15 mm thick and the total length of mould was 780 mm. The mould carried sinusoidal oscillation with constant stroke 11 mm and frequency-dependent casting speed. In this study, there are two moulds, referred to mould 1 and mould 2, were investigated detailed. The metal level detection system used radioactive source and the metal level was controlled by adjusting casting speed. The mould powder was fed manually, which required the operators guarantee a uniform distribution of powder. The relevant machine specifications and experimental operating conditions were listed in Table 1. Total four types of steels were cast during the plant trial listed in Table 2.

3. Results and Discussion

3.1. Metal Level Fluctuations

It is known that metal level fluctuations can give rise to...
longitudinal facial cracks in slabs, transverse depressions, bleeds and laps in bloom and billet casting, and offsquare-ness. And local variations in meniscus position can result in non-uniform shell strand formation.\textsuperscript{15} A method that the use of a submerged entry nozzle (SEN) to transfer liquid steel to the mould would inherently improve meniscus stability, since air entrainment between tundish and mould is prevented. Pinheiro et al.\textsuperscript{16} has compared the casting speed and metal level signal obtained with oil and mould powder lubrication during billets casting. The compared result indicates that the stability of the metal level has been improved by using a submerged entry nozzle (SEN) and mould powder lubrication.

Figure 2 shows the casting speed and metal level variations with casting time obtained with mould powder lubrication during round billets casting. The casting speed profiles follow the metal level signals quite closely with a small time lag. In general, thermocouples are more sensitive to local metal level fluctuations than the metal level sensor that responds to mean changes in level detected by the radioactive source. Although the radioactive metal level sensor is adequate for detecting global level changes, thermocouples embedded in the mould wall are more useful in detecting local metal fluctuations and thus, the formation of defects. Figure 3 illustrates, for mould 2, the mould cooling water temperature increase, and the temperature of hot face and heat flux measurements along the mould height against casting time in inner arc. It can be seen that the heat transfer is fluctuant with casing time under identical casting parameters. The thermal signal fluctuations are attributed to two types: (i) a high frequency fluctuation, which gives local variations in temperature of magnitude less than 10 K, and which is attributed to electrical noise in the signal and (ii) medium frequency fluctuation with temperature variations typically in excess of 10 K.\textsuperscript{17} It is evident that fluctuation of 1L belongs to the former type in opposition with 2L–6L that belongs to the latter type that is clearly a result of metal level fluctuations.

### 3.2. Heat Transfer Profiles during Casting

#### 3.2.1. Profiles of Longitudinal Mould Temperature and Heat Flux

Typical profiles of time-averaged temperature in the hot face of mould and heat flux along mould longitudinal height in inner arc, which was denoted 0° when thermocouples were embedded in the mould wall, were shown in Fig. 4. The temperature of mould wall is not uniform along its length that reflects a considerable variation in the heat-transfer rate from the steel shell to the mould. Generally, the highest heat flux should be obtained at the meniscus region.\textsuperscript{2,5,18} But the data in this experiment do not show the tendency. This may be attributed to the thermocouple position particularly of the hot faces located at 6 mm from the...
hot surface, which is not close enough to the hot face of the mould. In the vicinity of the meniscus, the heat flux is low, because there is a strong upward component of heat conduction toward the cold free board zone, and the straight port of submerged entry nozzle and the immersion depth are the other non-negligible reasons.\textsuperscript{11)} The temperature increases abruptly from the top of the mould until it reaches its maximum value approximately 70–110 mm below the meniscus that is located 77 mm below the top of the mould.\textsuperscript{11,12)} In this region, it is very sensitive to the operational parameters and varies highly compared with that in other places. The drop in mould temperature presumably results from a combination of increased shell/mould gap width and thickening solid shell as well as declining temperature driving force. At 365 mm from the top of the mould, the temperature sometimes rebounds a little, which is associated with a change of mould taper, and the taper is excessive for some steel grades to reduce the gap size between strand and mould. The rise in temperature towards the bottom of the mould may be due to excessive taper which forces the mould wall against the steel shell so that the heat transfer rate increases locally. The rebounds of temperature at the mould outlet have been also observed in slabs and billets reported by Mahapatra et al.\textsuperscript{2)} and Pinheiro et al.,\textsuperscript{5)} respectively. Detailed analysis of heat flux profiles, which have been discussed elsewhere,\textsuperscript{11,12)} are similar to that of temperature.

Variations of the longitudinal temperature and heat flux shown in Fig. 4 suggest that the standard deviation be a good index to characterize the nature of heat transfer fluctuations. A peak in the absolute value of standard deviation also occurs approximately at 70–110 mm below the meniscus. Mahapatra et al.\textsuperscript{2)} reported a maximum standard deviation of 2.1 K for raw data, without any filtration technique to eliminate the influence of casting speed and metal level variation during the slabs casting, and the standard deviation of the thermocouples was reduced to 4–5 K after filtering their mould temperature data. Pinheiro et al.\textsuperscript{5)} reported a maximum standard deviation of 13.5 K near the meniscus during billets casting. Therefore, the location of a maximum standard deviation for round billets, where maximum standard deviations of temperature and heat flux are approximately 10 K and 420 kW/m\textsuperscript{2} respectively. In the present study, the standard deviations of temperature and heat flux for the 1L thermocouple varied under 3 K and 30 kW/m\textsuperscript{2} respectively, as previously mentioned this was attributed to electrical noise.

3.2.2. Profiles of Circumferential Mould Temperature and Heat Flux in Different Mould Installations

Theoretically, the temperature and heat flux should not vary significantly around the mould circumference at the same height below the mould top. The measurements of the temperature and heat flux along the circumferential direction at various mould layers conducted in mould 2 experimentally have been investigated in the previous work.\textsuperscript{12)} Heat transfer is obviously extremely non-uniform along the circumferential direction.\textsuperscript{12)} In the present study, the measurements of temperature in the hot face of mould and heat flux along the circumferential direction at 2L were also investigated in mould 1 as shown in Fig. 5, where the values at 2L1, 2L5 and 2L6 are much higher than those at 2L2, 2L3 and 2L4. Furthermore, the local temperatures and heat flux at 2L vary with time, but maintain certain characteristic in the same mould installation as shown in Fig. 5. There are 256 groups of temperature and heat flux against casting time in Figs. 5(a) and 5(b), respectively. The figures show that temperature and heat flux are fluctuant with casting time even in the same monitoring point under the identical operational parameter. Furthermore, it can be seen that the heat transfer is fluctuant with casting time at degree 0° of 2L in Fig. 3, too. It can be also seen that the heat transfer in the mould are influenced significantly by different mould installations by comparing the heat transfer profiles of Fig. 5 with those of Ref. 12. In normal production, temperature and heat flux share the similar profiles along the mould circumference at the same height. If there is scale on the cold face of the mould, the trends of local temperature and heat flux are not the same any more, which will be discussed below in detail.

3.3. Mould Thermal Responses on Operational Parameters

3.3.1. Steel Carbon Content

The defects such as ofssquareness and transverse depressions are sensitive to steel carbon grade, especially for medium carbon grades.\textsuperscript{19,20)} In this study, two carbon composition steels referred to 0.19% C and 0.45% C as listed in Table 2 were used to discuss the influence of carbon content on heat transfer as shown in Fig. 6. Figure 6(a) shows...
the casting speed and tundish temperature as a function of casting time for one of these tests, in a sequence of the two heats. For a casting time of 28 min, the steel carbon grade was changed from 0.19% C to 0.45% C.

Figure 6(b) shows for the same trial the relative temperature and heat flux at 2L and 6L and (c) relative temperature and heat flux at 2L and 6L in inner arc during steel carbon grades change.

Figure 7 shows the variation of average mould water heat transfer with increasing casting speed for various carbon grade contents.

have been conducted to investigate the influence of carbon content on the heat flux, thus the billet quality. Grilli et al. found that heat flux in the mould for steel with carbon concentration below 0.25% was lower for medium carbon steel. Shrinkage of the solid shell near the meniscus occurred owing to the solid-state δ to γ phase transformation for lower carbon grade. Therefore, the gap was formed and provided sufficient thermal resistance to decrease heat transfer from the mould to the mould cooling water.

Figure 6(c) illustrates the variability of temperature and heat flux at 2L and 6L in inner arc. The value of variability is calculated as the relative standard deviation of the temperature and heat flux for each minute. Figure 6(c) shows that the variability of heat transfer decreases after the change of steel carbon grade at casting time of 28 min due to the high heat transfer as denominator in definition of variability ratio, which agrees with the results reported by Haers et al.

3.3.2. Casting Speed

Previous studies have found that the increasing casting speed causes the mean mould heat transfer to increase. Figure 7 shows that increasing casting speeds lead to increase in average heat transfer obtained from the water temperature difference between the inlet and outlet, particularly at higher carbon contents. The increased heat transfer at higher casting speed arises for three reasons. First, the shorter residence time of the steel at high casting speed results in thinner shells that deform easily under the ferrostatic pressure, ultimately reducing the mould/strand gap. Second, these shorter residence times result in hotter billet surface temperatures, which increase the driving force for heat flow. Third, there is less thermal contracting at these hotter strand shell temperatures, which may lead to intimate mould/strand contact by not contributing to the size of the gap.

3.3.3. Mould Oscillation Frequency

The mould oscillation frequency was changed from 150 to 180 cycle/min for 0.19% C with powder lubrication, the influences of this change on the mould heat transfer around mould circumference at 2L are shown in Figs. 8(a) and 8(b). The effects of mould oscillation frequency which was changed from 150 to 170 cycle/min with powder lubrication
when carbon grade 0.45% C was cast are shown in Figs. 8(c) and 8(d). It can be clearly seen that the mould wall temperature and heat flux increase with an increasing oscillation frequency. An increase in mould oscillation frequency decreases mould powder consumption, resulting in reducing the lubricating film between the mould and strand, and also reduce the negative strip time, which reduces the oscillation mark depth. Both effects lead to a decrease in the local mould/strand gap with a consequent increase in mould heat transfer.27,28) The influence of mould oscillation frequency on mould heat transfer observed in this study agrees with observations reported by Pinheiro et al.5) and Kumar.29) Kumar29) observed an increase in mould heat transfer when the mould oscillation frequency was increased from 100 to 160 cycle/min. Pinheiro et al.5) reported that mould heat transfer increased by about 8% when mould oscillation frequency was increased from 150 to 170 cycle/min. The studies conducted by Pinheiro et al. and Kumar were concerned with billets casting with powder and oil lubrication, respectively. Kumar29) attributed the enhancement in heat transfer to a decrease in the depth of oscillation marks, therefore, a narrower mould/strand gap. Pinheiro et al.5) considered that mould fluxes were much more effective as casting lubricants than oil after comparison and concluded that the magnitude of mould/strand interactions should not play such an important role as in the case of oil lubrication, therefore, the increase in heat flux when mould oscillation frequency increasing with mould flux lubrication should be caused by a decrease in the thickness of the flux film. In this plant trial, mould oscillation frequency is determined from casting speed. Therefore, the higher frequency corresponding to higher casting speed is the main interpretation for heat transfer increase with increasing mould oscillation frequency.

3.4. Responses of Heat Transfer with Scale

Scale on the cold side of a mould has an important effect on the mould heat transfer.30) The deformation of mould and rhomboidity can be detected when scale occurring.31,32) Usually, the measured temperature profile is similar to that of the measured heat flux along the mould circumference at the same height, as shown in Fig. 5. The mould inspection performed after the trial corresponding to Fig. 5 showed there was scale in the area at which a thermocouple in 4-array at 2L was located. In the following, the scale formation and its influence on heat transfer in mould 2 will be discussed detailed.

Figures 9 and 10 illustrate the heat flux and temperature at 2L and 6L in 1 and 4-array respectively, together with
corresponding operational parameters such as casting speed, mould level, tundish temperature and mould oscillation frequency against casting time. The casting time of Fig. 10 is about 24 h after that of Fig. 9 with the same mould, and the casting times of Figs. 9 and 10 are both part of the whole casting time after reaching steady state in the continuous casting process. It is obvious that the profiles of heat flux and temperature are almost identical at any height of the mould in Fig. 9 while quite different in Fig. 10. No scale may have been formed in the casting of Fig. 9 due to the identical thermal data as well as relatively earlier stage of casting. Scale formation at the very start point of Fig. 10 is empirically possible. The hot face temperature at 4-array in Fig. 10, is high up to 160–170°C greater than that at 1-array, however, the heat flux is low, only 150–2 000 kW/m², much less than that at 1-array, almost 2 300–4 500 kW/m². The mould temperature of hot face is the highest at the location where the mould heat flux is not a maximum. The mould inspection performed after the trial corresponding to Fig. 10 showed there was scale in the area at which a thermocouple in 4-array at 2L was located. It is known that the main content of the scale is deposition such as CaCO₃, the solubility of which decreases with increasing temperature. In the present paper, the cold face temperature at 2L4C in Fig. 10(b) reaches about 150°C which may imply boiling. Thereby, the higher temperature leads to more CaCO₃ sticking to the mould cold face. The thermal conductivity of CaCO₃ is below 1.16 W/(m·K) much less than 380 W/(m·K) of copper. Scale formation can lead to a considerable thermal resistance between the mould and cooling water. Heat transfer at 2L1H is fluctuant before 700 s in Fig. 10. This may show an evidence of the scale formation gradually proceeding and uneven distribution on the cold face of mould. Subsequently, there is more and more scale to supply considering thermal resistance to decrease heat transfer from the mould to the cooling water after 700 s. As estimated above, the scale formation may have a function only to enhance the unbalanced heat transfer. Therefore, what brings scale formation has not been understood at the moment. Further studies on how the scale is initiated will be extensively made in the near future.

Considering the importance of abnormal heat transfer, a method called correlation coefficient of heat flux and temperature (CCHT) is introduced to analyze the influence of scale formation on unbalanced heat transfer in quantity. The absolute magnitude of CCHT is utilized to appraise similarity of temperature and heat flux around 2L mould perimeter. The absolute value of CCHT close to 1 means that the temperature is parallel to that of heat flux along the circumferential mould, which means on the absence of scale in normal production. However, when the absolute value of CCHT deviates far from 1, there may be scale on the cold face of mould. The equation of CCHT is given by:

$$\gamma_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}}$$

Wherein $\gamma_{xy}$ correlation coefficient, $x_i$ and $y_i$ are two series of data, $\bar{x}$ and $\bar{y}$ are the average of them, respectively. The two series of independent variables are substituted by average temperature in the hot face and heat flux around 2L perimeter of the mould.

The profiles of average heat flux and temperature around 2L mould circumference and their corresponding CCHT are shown in Fig. 11. Figure 11(a) is as the same plant trial as Fig. 9 and the CCHT is 0.9842, which means there is on the absence of scale on the cold face of mould. The absolute value of CCHT close to 1 means that the temperature is parallel to that of heat flux along the circumferential mould, which means on the absence of scale in normal production. However, when the absolute value of CCHT deviates far from 1, there may be scale on the cold face of mould. The equation of CCHT is given by:

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correlation with thermal resistance between shell and mould to some extent before the disappearance of liquid slag. It can be seen that the correlation is a good tool for appraising the similarity of two groups of data that have intrinsic relations. In the present work, the phenomenon that the CCHT decreases with the increasing casting time clarifies that the similarity of heat flux and temperature becomes smaller. It could be concluded that there is more and more scale on the cold face of mould with casting time in abnormal production. This has been confirmed after experiments through inspecting tested moulds and water jackets. Since the CCHT is based on the transverse heat flux and temperature.

Fig. 11. Distributions of average heat flux and temperature in hot face around the mould perimeter as well as corresponding correlation coefficient at 2L (a) for the same trial as Fig. 9 on the absence of scale and (b)–(f) for the same trial as Fig. 10 on the presence of scale.

<table>
<thead>
<tr>
<th>Production Type</th>
<th>Casting Speed (m/min)</th>
<th>Tundish Temperature (°C)</th>
<th>Average Mould Level (mm)</th>
<th>Mould Oscillation Frequency (cpm)</th>
<th>EMS Current (A)</th>
<th>EMS Frequency (Hz)</th>
<th>Correlation Coefficient (CCHT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.616</td>
<td>1516</td>
<td>75.6</td>
<td>190.5</td>
<td>288</td>
<td>4.9</td>
<td>0.9842</td>
</tr>
<tr>
<td>b</td>
<td>2.201</td>
<td>1546</td>
<td>80.5</td>
<td>160.5</td>
<td>258</td>
<td>4.9</td>
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<tr>
<td>c</td>
<td>2.258</td>
<td>1543</td>
<td>81.9</td>
<td>164.4</td>
<td>258</td>
<td>4.9</td>
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<tr>
<td>d</td>
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<td>1552</td>
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<td>258</td>
<td>4.9</td>
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<tr>
<td>e</td>
<td>2.450</td>
<td>1545</td>
<td>79.5</td>
<td>178.4</td>
<td>258</td>
<td>4.9</td>
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<tr>
<td>f</td>
<td>2.661</td>
<td>1537</td>
<td>82.4</td>
<td>193.8</td>
<td>258</td>
<td>4.9</td>
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</table>
ture, it can be postulated the probability of occurrence for transverse crack will enhance when the CCHT values are far from 1, which results from unbalanced heat transfer in the circumferential mould. Further studies on how the CCHT is related to slab quality will be extensively made in the near future.

4. Conclusion

Although many studies involving oil or powder lubrication in the slabs/billets mould of continuous casting process have been researched, there have been relatively few studies delineating the thermal responses of the round billets. The mould heat transfer phenomena, along circumferential and longitudinal directions, have been detected through the instrumented mould study. The influences of steel carbon contents, casting speeds, mould oscillation frequency, especially abnormal characteristics of scale on mould heat transfer have been examined. The main conclusions of the present study are summarized as follows:

1) Both local temperatures and heat flux, along the mould circumferential and longitudinal directions, have been observed during casting. The circumferential heat transfer is non-uniform, which is dependent on the different moulds installation statuses.

2) The correlation coefficient of average heat flux and temperature (CCHT) in the hot face of mould is introduced to analyze the influence of scale on abnormal heat transfer in quantity. Comparisons of temperature and heat flux profiles on absence of scale and presence of scale have been done on the basis of absolute value of CCHT.

3) The mould temperature and heat flux increase with increasing carbon content of steel and casting speed. The temperatures and heat flux are higher with an oscillation frequency of 180 cycle/min than those of 150 cycle/min for carbon grade of 0.19% C and also higher with an oscillation frequency of 170 cycle/min than those of 150 cycle/min for carbon grade of 0.45% C owing to high casting speed mainly in this plant trial.

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