1. Introduction

The water spray with phase change heat transfer has been an attractive method of cooling due to high heat transfer coefficient especially in hot steelmaking processes which include the Runout-table cooling of hot rolled mill, the accelerated cooling of plate mill, and the bar cooling of wire-rod mill. Spray cooling is well known as the representative cooling methods of the hot steelmaking industries. The surface roughness of the steel can play a significant role in the cooling processes, and thus should not be significantly neglected. Most of commercial steel products like as the hot rolled and plate steel have an average roughness height of 12.5–50 μm. Surface roughness effects on the stagnation-point heat transfer using an impinging liquid jet were investigated for nine rough surfaces with root-mean-square average roughness heights ranging from 4.7 to 28.2 μm and correlated for smooth and rough surfaces. Recently, the heating cooling process is required to produce the high-tensile steel like as TMCP steel, so the surface of a current steel products can be a little rougher than an as-rolled steel product.

The current study is mainly motivated by the fact that most cooling and quenching processes of steelmaking require the exact heat flux curve and heat transfer coefficient during the water cooling process. In case of plate mill, an accelerated cooling is nominally started from the austenitic temperature of 800°C to the finish cooling temperature of 400°C, which depends on its target metallurgy. However there were few studies on the forced flow boiling characteristics that could be applied to the water spray cooling of the industrial steelmaking applications.

Most conventional hot steel cooling experiments in the laboratories were carried out to heat up a stainless steel plate using an electric muffle furnace in which heating method was needed for much consuming time, money, and experimental difficulties. Hatta et al. used the stainless steel plate of 200 mm × 200 mm × 10 mm in size for their cooling experiments.

In this study, the local heat flux measurements were introduced by a novel experimental technique in which test block assemblies with cartridge heaters, thermocouples were used to measure the heat flux distribution on the surface of hot steel plate as a function of heat flux gauge. The roles of surface roughness on heat transfer are presented for well-characterized four rough surfaces with average rms roughness heights ranging from 40 to 80 μm. The results show that the local heat transfer for the rough surface is compared with that for a smooth surface. Finally the heat transfer enhancement mechanism on rough surface can be investigated by the different boiling phenomena.

KEY WORDS: water spray cooling; surface roughness; boiling; hot steel plate.

2. Experimental Apparatus and Procedures

2.1. Experimental Apparatus

Experiments were carried out to determine the local heat flux at the center of water spray impinging on a rough surface. The experimental apparatus is illustrated schematically in Fig. 1 and consists of a flow loop and an electrically heated test block with rough surfaces from 40 to 80 μm roughness height. A water spray impinges vertically downward and strikes a uniformly heated surface on which temperature measurements are made. The nozzle-to-target spacing was held constant at 360 mm and the water temper-
ature was nearly kept constant at 20°C. An EVERLOY 1/4 KS FHS 0865 with inner diameter 2.9 mm spray nozzle was used to produce the fullcone-type spray flow patterns. During the experiments, the water flow rate was kept at 6.0 LPM as determined from rotameter connected in the flow loop. The Reynolds numbers that calculated by flow rates were approximately 49 000. Its measurement uncertainty reached a maximum of $\pm 3\%$ for the volumetric flow rate measurement and $\pm 4\%$ for the Reynolds number.

A test assembly is fabricated as shown in Figs. 2(a) and 2(b). The test assembly consists of the test block, the cartridge heaters and the thermocouples, and has a function of heat flux gauge during experiments. The water spray impinges vertically onto a heated test block, which is made of a SUS304 which avoids phase-transformation heat generation happens at most of carbon steels. The test block has a height of 60 mm and a diameter of 100 mm. The test block was designed to reduce geometric deformation after repeated experiment, because the aspect ratio of the block was almost 1.67, which applied to less plastic deformations. So the test block can be repeatedly used in the high temperature heating/cooling experiments more than 20 times. The sixteen heaters of a WATLOW HT Firerod cartridge heater with 12.7 mm diameter were installed into the test block and were used to heat the test block electrically up to high temperature of about 900°C. Nine K-type (Chromel-Alumel) thermocouples of 0.5 mm thick were installed to measure temperatures at distinct 9 points as shown in Fig. 3. Seven thermocouples are positioned at the center of the block along thickness direction. No. 1 and No. 2 thermocouple is respectively located at 1 mm and 2 mm apart from the bottom surface, No. 3 thermocouple is located at the quarter of the block (15 mm apart from the bottom surface), and No. 4 is located at the center of the block. No. 7, 6, and 5 thermocouples are installed at the top surface. No. 8 and 9 thermocouples are made to check radial temperature change of the block. No. 8 and 9 thermocouple is installed at the 30 mm and 15 mm from the No. 4 along the radial direction, respectively. As the lateral face of heating block is covered by the insulating materials of Cerakwool®, the temperature of No. 8 and No. 9 is revealed to be nearly identical to that of No. 4 as shown in Fig. 5(c), so the radial temperature change might be neglected through the experiment. Then the one-dimensional heat transfer process along the thickness direction was eventually made in the heat flux measurement.

Before and after experiments, a prior calibration of the thermocouples was performed by comparison to the platinum resistance thermometer. The final uncertainty in the measured temperature was $\pm 0.1°C$. Detailed information of the test assembly, cartridge heater, calibration procedures, and the uncertainty analysis is given by Lee.8)

2.2. Rough Surface Characterization

The rough surfaces were manufactured by corrosive patterning a 3 cm diameter central portion of the test block, which is attempting to simulate homogeneous roughness in
by Beck et al.\textsuperscript{9,10} was performed to determine the local heat fluxes on the surface during the transient water spray cooling experiments.

It is necessary to have a mathematical model of the heat transfer process to estimate the surface heat flux information. Assuming that the mathematical model of temperature distribution is described by one-dimensional heat equation along the plate thickness, we get

\begin{equation}
\rho c_p(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) \tag{1}
\end{equation}

\begin{equation}
T = T(t, x) \quad (t>0, \; 0<x<L) \tag{2}
\end{equation}

The boundary conditions are

\begin{equation}
-k(T) \frac{\partial T}{\partial x} = q_{\text{bottom}}(t) \quad \text{at} \; x = 0 \tag{3}
\end{equation}

\begin{equation}
-k(T) \frac{\partial T}{\partial x} = q_{\text{top}}(t) \quad \text{at} \; x = L \tag{4}
\end{equation}

The initial conditions are

\begin{equation}
T(t, x) = \phi(x) \quad \text{at} \; t=0 \tag{5}
\end{equation}

Where \( T(t, x) \) is the plate temperature distribution at the point along the thickness direction \( x \). As mentioned in previous chapter, the lateral heat conduction was assumed to be neglected in this study.

The direct heat flux measurement method using Newton's cooling law was also applied to validate the IHCP numerical formulation.

\begin{equation}
q = -k \frac{\partial T}{\partial x} = -k \frac{(T_{\text{surface}} - T_{\text{No.1}})}{\Delta x} \quad \text{at top surface} \tag{6}
\end{equation}

\begin{equation}
q = -k \frac{\partial T}{\partial x} = -k \frac{(T_{\text{surface}} - T_{\text{No.1}})}{\Delta x} \quad \text{at bottom surface} \tag{7}
\end{equation}

Where the temperature difference was achieved by the estimated surface temperature by IHCP and measured temperature very close to surface.

3. Results and Discussion

3.1. Temperature Profile

The time-dependent temperature distribution after impacting water spray is shown in Fig. 5. The temperature is seen to change with cooling time. The spray cooling started at 900°C. It is seen that the temperature decreases similarly for T1, T2, and T3 which locations are very close to the surface. T4 and T5 exhibits monotonically decreases in temperature through whole spray cooling.

The rapid temperature drop occurs at surface temperature of 400°C for all tested surfaces. The temperature close to the surface (T1, T2, and T3) reaches its sudden decrease in temperature at approximately 200 s for S0 surface (smooth surface) and at approximately 190 s for S3 surface, respectively, as shown in Figs. 5(a) and 5(b). This is characterized by a termination of a film boiling as the water spray wets the heated surface directly. Large rms roughness height for the S3 sur-
face was occurred to exhibit earlier transition boiling since rough surface has greater effective heat transfer area than smooth surface.

The radial temperature variation of test block is shown in Fig. 5(c). The temperature difference between No. 8 and No. 4 thermocouple is seen to about 5%. As mentioned before, the radial temperature variation might be relatively neglected through the water spray cooling experiments.

3.2. Visualization of Boiling

The time resolved evolution of the water spray cooling viewed from top-side with the rough surface of the S3 are shown in Fig. 6. These consecutive images of flow visualization on the heated rough surface were captured from the synchronized high-definition camcorder (SONY HDR-SR7) during the water spray cooling experiment. The surface on the heated test block is seen to change with time.

Though Fig. 6(a) does not exhibit any surface wettings, however the surface wetting starts to occur in Fig. 6(b), which perfectly corresponds at 191 s after impinging water spray. After 190 s, the water spray droplets start to direct contact the heated surface, which means the termination of a film boiling. So the presence of surface wetting caused its temperature to rapidly decrease as shown in Fig. 5.

The very good agreement between the sudden temperature decrease in Fig. 5 and the visualization of boiling in Fig. 6 indicates that the better understanding of boiling mechanism during water spray cooling might be achieved by the visualization of boiling.

3.3. Heat Transfer Characteristics

Typical heat flux curves for the four rough surfaces of S0, S1, S2, and S3 are shown in Fig. 7. The surface number of S0 means a smooth surface which has a 0.41 μm. S1, S2 and S3 has an average of root-mean-square roughness height of 40, 60, 80 μm, respectively.

The critical heat flux (CHF) of this experiment is observed to exist within 240–300°C, which is nearly identical to that of a flow boiling. It is seen that the CHF value increases with increasing surface roughness height, as would be expected. The CHF values of rough surfaces are much greater than those of smooth surface, which exhibits about 20% increase in S3 compared to S0. The CHF is well known as to be highly dependent of surface characteristics which are explained by the effective area of surface.

The heat transfer coefficient distributions along the surface temperature are shown in Fig. 8. As the surface temperatures for all rough surfaces reach at 400°C, the heat transfer coefficient starts to sudden increase. Within transi-
tion boiling regime, namely the surface temperature ranged from 240–420°C, the rougher surfaces have much higher heat transfer coefficient than smooth surfaces. In this regime, the maximum heat transfer coefficient differences between the S3 and the S0 were as large as 200%. It is of interest to note that the relationship between the film, transition, and nucleate boiling is highly dependent on the surface roughness conditions. This behavior can be explained by examining the effective thermal boundary layer thickness as determined from the smooth wall Nusselt number expression. Generally the thermal boundary layer thickness (δt) was reported that its magnitude was approximately less than 10 µm in case of the forced convection heat transfer by water spray. The roughness height, R_q, is likely to have a great impact on heat transfer enhancement under conditions for which δt is much smaller, as its surface protrusion into the thermal boundary layer is greater. Since the roughness height of S1, S2, and S3 is much greater than the effective thermal boundary layer thickness, a surface protrusion as shown in surface profiles of Fig. 4 might disrupt thin thermal boundary layer, and thus heat transfer can be significantly increased by the presence of surface roughness.

The estimated values of heat flux determined from the IHCP are compared with the directed measured values as shown in Fig. 9. It is observed that the direct measured values are somewhat smaller than predicted. The good agreement between the IHCP estimation and the direct measurement used in this study predicts quite well the variation in heat flux.

4. Conclusion

A novel experimental technique using high temperature supply cartridge heaters has been used to examine the effects of surface roughness, and the further understanding of the forced flow boiling. This experimental method provided a great advantage of measurement which can be explained by (1) re-use of test block assembly up to 20 times, (2) simple setup as a heat flux gauge, which are innovatively compared to conventional forced convection cooling experiments. Heat transfer can be significantly increased by the presence of surface roughness elements, which can disrupt the thin boundary layer. Increases in heat transfer coefficient over that of a smooth surface were as large as 200%. The good agreement between the IHCP estimation and the direct measurement used in this study predicts quite well the variation in heat flux.

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