Heat Transfer Characteristic of Slit Nozzle Impingement on High-temperature Plate Surface

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Heat transfer mechanism of a slit jet impingement was thoroughly studied to improve capacity and uniformity of a hot steel strip/plate during its ultrafast cooling or quenching. The impact angle has a significant influence on the heat transfer characteristics of the stationary slit jet impinging process. Heat transfer capability and rewetting front propagation, which include such parameters as $q_{\text{max}}$, $t_{\text{MHF}}$, and $T_{\text{MHF}}$, differ significantly between the upstream and downstream regions. Parallel flow and intense sputtering in the downstream region are apparent for the forward-moving inclined slit jet impingement cooling process. The antiparallel flow in the upstream region is thinner, and the sputtering is reduced and is relatively stable. As the plate moves forward, the wetting front expands and forms almost a straight line with synchronized and uniform heat transfer. The inclined angle increases from 0 to 45°, which significantly increases the heat transfer intensity and shortens the time to nucleate boiling stage as well as the width of the transitional boiling region. A higher moving velocity reduces and promotes $q_{\text{max}}$ moving to the downstream region.

KEY WORDS: ultra-fast cooling; heat transfer; slit jet impingement; boiling phenomenon.

1. Introduction

Controlled cooling is widely applied in steel plate/strip production. It helps to improve the microstructure and mechanical properties of a rolled steel sheet. As shown in Fig. 1, an ultrafast cooling (UFC) system on a run-out table in a factory uses jet impinging technology with high heat efficiency.\cite{1,2} Heat transfer characteristics are mainly affected by the jet parameters, fluid properties, steel plate properties, environmental factors, etc. and they strongly affect cooling ability and uniformity. These parameters also define model accuracy, thus, their thorough understanding is crucial for the cooling system optimization.

Numerous studies have been reported on round jet impingement heat transfer characteristics and what affects them. Karwa et al.\cite{3} studied boiling heat transfer and identified the boiling regimes by snapshot observations and boiling-curve analysis. Hauksson et al.\cite{4} measured the surface and internal temperatures of flat steel plates and discussed how water flow rate and subcooling influence overall heat transfer. Chester et al.\cite{5} investigated the effects of inclination angle and flow rate on the bottom jet impinging process. Boiling characteristics and heat extraction histories for different nozzle inclined angles and flow rates were also studied. Moving conditions also seriously affect the heat transfer process. According to Zumbrunnen et al.\cite{6,7} the plate moving speed strongly influences the boundary layer development in both gas and liquid phases. The surface motion has a minor effect on the single-phase forced convection adjacent to the impinging point. Their lat-
ter research works provided observations of the heat transfer characteristics of round jet impingement cooling.

Several research groups experimentally investigated free-surface and submerged heat transfer characteristics of the flow field during the slit jet impingement process, such as surface pressure, heat flux distribution and variety as well as local heat transfer coefficient during the turbulent or laminar impingement cooling. The effect of the Reynolds number, water jet flow rate, inclined jet impingement angle, nozzle-to-surface spacing and nozzle exit hydraulic diameters on the fluid flow and heat transfer distribution were studied. Among them, the inclined jet impingement angle was the focus of many reports studying changes of the heat transfer parameters. The results showed that the region of maximum heat transfer shifts toward the uphill side of the plate, and the maximum Nusselt number decreases as the inclination angle decreases.

A lot of experimental and numerical studies of the slit jet impinging process in a moving state have been reported as well. Ai et al. pointed out that a moving nozzle enhances heat transfer and temperature uniformity more than a fixed nozzle. Benmouhoub et al. numerically investigated the global structure and heat transfer for a confined slot jet impinging on a moving surface with a range of jet exit Re, plate velocity ratios, and jet inclination. The simulation results showed that the structures of the flow and heat transfer were strongly affected by a moving impingement wall.

Though the above-mentioned researchers had studied the influence of parameters on heat transfer, there were few researches about the slit jet impinging on a moving surface with the inclined slit nozzle. In the present work, the surface heat flux, water flow structure and the heat transfer area distribution were investigated with the inclined slit jet impingement on a moving plate. Our results will help to optimize cooling equipment and controlled parameters for the industrial-scale plate/strip cooling technology.

2. Experimental Setup and Procedure

2.1. Experimental Setup

Experimental setup consisted of a water tank, water supply pump, thermometer, pressure meter, thermocouples, data acquisition system, digital camera and a test chamber (see Fig. 2). Cooling water was pumped at 1.5–30 L/min range. The nozzle height and angle adjustment ranges were −400–400 mm and −90–90°, respectively.

Dimensions of the AISI 304L steel plate with excellent antioxidant properties made out of austenite were 20×80×150 mm (see Fig. 2). Surfaces of the steel plates were cleaned with methanol and then left in the as-rolled conditions. Then, seven 3-mm in diameter K-type chromel-alumel thermocouples were equidistantly embedded 2.5 mm below the plate surface and 30 mm deep. We used high-temperature glue to seal the narrow gap between the thermocouples and the plate to achieve as accurate temperature measurements as possible. Ten-channel data acquisition system was used to collect the data from the thermocouples. The slit jet impingement prototype is shown in Fig. 3, and a schematic of the plate-and-nozzle relative movement is presented in Fig. 4. Specific experimental parameters included a jet with the slit length (L = 80 mm), starting cooling temperature (TSC = 700°C), water temperature (TW = 10°C)
and impingement height (H = 200 mm). The temperature had to be above 700°C to compensate for the heat loss.

We properly arranged jet angle on the platform using a protractor and a ruler. Then, the steel plate with the desirable temperature was placed in the prepositioned groove, after which water supply system was quickly turned on as the plate was reaching the targeted temperature. Temperatures were thoroughly recorded throughout the whole procedure, and a video camera was used to record the cooling process.

Table 1 summarizes all experimental conditions tested in our study. Calculations of the surface heat flux and temperature were performed using one-dimensional heat equation in the thickness direction as shown in Eq. (1). Initial and boundary conditions are shown in Eqs. (2)–(4):

\[
\rho c_p(T) \frac{dT}{dt} = \frac{\partial}{\partial x} \left( k \frac{dT}{dx} \right) \text{...............(1)},
\]

where \(T = T(x,t)\) \((t > 0, 0 < x < h)\).

The equations for the boundary conditions are

\[-k \frac{dT}{dx} = q_{\text{bottom}}(t) \text{ at } x = 0 \text{ ..............(2)},
\]

\[-k \frac{dT}{dx} = q_{\text{top}}(t) \text{ at } x = h \text{ ..............(3)}.\]

The equation for the initial condition is

\[T(t,x) = T_0(x) \text{ at } t = 0 \text{ ..............(4)},\]

where \(\alpha = \frac{k}{\rho c_p}\) is thermal conductivity coefficient, \(T\) is plate temperature, \(k\) is thermal conductivity, \(\rho\) is density, \(c_p\) is the specific heat, \(t\) is cooling time and \(x\) is a coordinate in thickness direction.

The finite difference method was employed to solve the heat conduction problem. The absolute value of the difference between measured and calculated values was \(\delta = 0.01^\circ\text{C}\).

2.2. Error Analysis

K-type thermocouples with the instrumental error of ±0.75% were used. Experimental temperature deviation of ±10°C relative to desired initial temperature was allowed. Relative error of the temperature acquisition system (GRAPHITEC GL220) was about ±0.5%. The jet flow accuracy was ±0.6 L/min. Initial water temperature was maintained at 10±1°C, however, it was difficult to control it during the experiments. The accuracy of the rewetting time depended on the video camera and was ±0.033 s. Accuracy of thermocouple position was ±0.5 mm.

3. Results and Discussion

3.1. Heat Transfer Characteristics of Stationary Slit Jet Impingement Process

3.1.1. Heat Transfer Region of Stationary Slit Jet Impingement Process

Figure 5 shows digital images of the cooling process with a 2-mm wide slit nozzle, 15 L/min jet flow and zero vertical impact angle. The cooling water impinged on the hot steel plate, forming a steam vaporization film on the surface of the hot plate, hindering the effective heat transfer between the liquid and the solid interface. At 0.07 s, a black line can be observed in the impinging zone. This corresponds to the wetted region, where the strongest heat transfer occurred. Significant two-sided sputtering can be observed in the dry zone. Distribution of the heat transfer area at any given time is shown in Fig. 6. The wetting front is typically a narrow transition zone and the dry zone is transformed into the wetting zone. The wetting front position \(r_w\) is in the transition heat transfer zone. \(P_{\text{nm}}\) characterizes the maximum heat flux density that occurs at the boundary between the nucleate boiling and the transition boiling heat transfer region, adjacent to the wetting front position \(r_w\). Typical distribution of the surface temperature \(T_s\) and the heat flux \(q_s\) with respect to the impact line distance \(r_w\) are shown in Fig. 6.

Figure 7 shows relative evolution of the surface temperature and the heat flux at \(d = -30\) mm with the 2-mm wide slit nozzle, 15 L/min jet flow and zero vertical impact angle. First, the surface heat flux increased slightly in film boiling stage I which is characterized by a stable layer of vapor that forms between the heated wall and the liquid, and then grew relatively fast in the transition boiling stage II, accompanied by the vapor film broken by the impinging water flow. When the transition boiling completely shifted to nucleate boiling, the heat flux reached its maximum, \(q_{\text{max}}\) where the most drastic temperature decrease occurred. With the decrease on the plate surface temperature, the heat transfer process successively entered nucleate boiling stage III with higher heat transfer coefficient (HTC), and single-phase force convection stage IV with lower HTC.

3.1.2. Effect of Impact Angle on Stationary Jet Impingement Process

Slit nozzle impact angle can effectively change the heat transfer characteristics and is typically used to flexibly adjust the cooling capacity and cooling uniformity of the system. The boiling curves at the impingement region (such as P4 thermocouple shown in Fig. 3) and the measured position \(d = \pm 30\) mm (P1 and P7 thermocouple) are presented in Fig. 8 for the stationary slit jet impinging process with an impact angles equal to 0, 15, 30 and 45°. Figures 8(a),

| Case | Initial temperature /°C | Slit width /mm | Height /cm | Jet flow /L/min | Jet angle /° | Nozzle speed /mm/s |
|------|--------------------------|----------------|-----------|----------------|-------------|-------------------|
| 1    | 700                      | 2              | 20        | 15             | 0           | 0                 |
| 2    | 700                      | 2              | 20        | 15             | 15          | 0                 |
| 3    | 700                      | 2              | 20        | 15             | 30          | 0                 |
| 4    | 700                      | 2              | 20        | 15             | 45          | 0                 |
| 5    | 700                      | 2              | 20        | 15             | 15          | 0                 |
| 6    | 700                      | 2              | 20        | 15             | 15          | 15                |
| 7    | 700                      | 2              | 20        | 15             | 15          | 10                |
| 8    | 700                      | 2              | 20        | 15             | 15          | 15                |
| 9    | 700                      | 2              | 20        | 15             | 15          | 20                |
| 10   | 700                      | 2              | 20        | 15             | 15          | 30                |
| 11   | 700                      | 2              | 20        | 15             | 15          | 45                |
| 12   | 700                      | 2              | 20        | 15             | 15          | 15                |
8(b) indicate that the heat flux in the stagnation region was similar to that in the vertical case 0°, with the \( q_{\text{max}} \) peak was equal to 4.42 MW/m² at 520°C surface temperature. In the parallel flow region, \( q_{\text{max}} \) was lower because the parallel flow velocity and superheat decreased as the cooling water started flowing outward.\(^{23,24} \) However, as shown in Figs. 8(c), 8(d), \( q_{\text{max}} \) in the downstream region (d = 30 mm) increased from 3.6 to 4.0 MW/m² as impact angle \( \alpha \)

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Fig. 5. Photographs of the stationary vertical slit jet impingement cooling process.

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Fig. 6. Heat transfer region distribution for the stationary vertical slit jet impingement cooling.

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Fig. 8. Boiling curves \( d = 0, 30, -30 \) from impinging lines for different impact angles.

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Fig. 9. Photographs of the cooling process of the moving inclined slit jet impingement at different times.

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Fig. 10. Schematic of the water flow structure and heat transfer region of the cooling process of the moving inclined slit jet impingement.
increased. As the surface temperature began approaching $q_{\text{max}}$, it slightly dropped from 400 to 378°C. Figures 8(e) and 8(f) show significant differences in the heat transfer capacity in the upstream zone ($d = -30 \text{ mm}$). $q_{\text{max}}$ decreased from 3.64 to 2.98 MW/m² and the corresponding surface temperature dropped from 358°C to 220°C because decreased water flow typically reduces the heat transfer ability at a high-temperature.25) And Fig. 8(g) shows the relationship between measured temperature and time on the surface of plate.

As shown in Figs. 8(a), 8(c), and 8(e), as the water jet hit the hot surface in the impact region, the rewetting process occurred at 0.06–0.08 s.26) $t_{\text{MHF}}$ at different impact angles was about 1.8 s, indicating that the heat transfer in the impact region quickly transitioned to the nucleate boiling stage. However, the wetting front propagation was severely delayed at distances far from the impact region. Because of the different kinetic energy of the parallel flow, $t_{\text{MHF}}$ and $t_{\text{MHF}}$ at symmetrical measured position in the upstream and downstream regions were different. In the downstream region, the inclination angle promoted spreading of the wetted area because of the larger kinetic energy of the parallel flow, which prevented boiling bubbles from accumulating at the wetting front and easily breaking through the stable vapor film.27) By contrast, the parallel flow energy in the upstream region was reduced, and the rewetting front propagation was significantly hindered.

### 3.2. Heat Transfer Characteristics of Moving Slit Jet Impingement Process

#### 3.2.1. Video Analysis of Moving Slit Jet Impingement Process

To simplify the discussion below, we define the following parameters as follows: “① vertical moving jet impingement” as an impact of the water flow perpendicular to the impinging on the surface of the steel sheet; “② forward moving jet impingement” as the plate moving in the same direction at the nozzle-tilting direction; “③ reverse moving jet impingement” indicates the plate moving in the opposite direction to the nozzle-tilting direction, as shown in Fig. 4. Figure 9 shows cooling process of the forward-moving jet impingement on a hot steel plate surface at 15° impact angle and 15 mm/s nozzle moving speed. At the initial stage, the cooling water sprayed out of the right edge of the plate. As the plate continued moving right, the impinging water instantly impacted the plate edge. Black rectangularly-shaped wetted area appeared on the hot plate surface shortly thereafter.

As the nozzle continued moving forward, the wetting front expanded accordingly, and its shape remained close to a straight line. The plate surface temperature in the right wetted region dropped rapidly. The water flow structure and heat transfer region distribution for the moving inclined slit of the jet impingement cooling process are depicted in Fig. 10. The impinging jet structure can be divided into three zones: free jet region, stagnation region and a wall jet region. The free jet region can be further divided into three regions: potential core region, developing zone and fully developed zone.28) If the initial jet velocity $U_0$ upon exiting increased to $U_{\text{max}}$ within the potential core, then the velocity decreased beyond the potential core. At the stagnation point the pressure is higher than the ambient pressure, resulting in a favorable pressure gradient that turns the flow to a direction parallel to plate, forming the wall jet region.29) The most distinctive and interesting feature of a wall jet is the two shear layers of different type: an inner layer, where the flow resembles that of the conventional boundary layer, and an outer layer, where the flow is similar to that of a free shear layer.30) The parallel flow and intense sputtering was apparent in the downstream region. Meanwhile, the opposite flow in the upstream region was thinner, had less sputtering and was stable. The small liquid accumulation region, the film boiling region, the transition boiling region, the nucleate boiling region and the single-phase force convection region were all distributed from left to right. These was significantly different from the stationary slit jet impingement cooling process.

The rewetting front and the maximum heat flux appeared close to the jet impinging line under the specified experimental conditions, similar to the one reported by Fujimoto et al.31) In this case, the uneven distribution of the water flow produced by the nozzle manufacturing accuracy had little effect on the heat transfer uniformity because of an intense heat exchange in the straight-line wetted front region. As a result, the heat transfer along the length of the slit nozzle was synchronous and uniform. It can be speculated that a rewetting process would occur in the upstream or downstream
parallel regions depending on the impact angle, jet velocity, water temperature, plate surface temperature and plate moving speed. Influence of all these parameters on the rewetting process will be further investigated in our future work.

Fig. 11. Heat flux curves for different impact angles.

Fig. 12. $q_{\text{max}}$ for different impact angles.

Fig. 13. $t_{\text{MHF}}-t_w$ and $t_{\text{MHF}}-r_w$ for different impact angles.

Fig. 14. Cooling process of the reverse moving jet impingement.

Fig. 15. Boiling curves at different nozzle moving speeds: 10 (a) and 20 (b) mm/s.

Fig. 16. $q_{\text{max}}$ (a) and $t_{\text{MHF}}-t_w$ and $t_{\text{MHF}}-r_w$ (b) for different moving speeds.
3.2.2. Effect of Impact Angle on Moving Slit Jet Impinging Process

During the moving slit jet impinging process, the upstream parallel flow will precontact with the hot plate surface and form a vapor film that prevents direct contact between the liquid and the solid. However, the relative movement hinders upward water flow and a hydraulic jump can be observed on the upstream front end.\(^{(35)}\) The slit jet moves from thermocouple 1 (P1) to thermocouple 7 (P7), the heat flux change ranges at 15 mm/s plate moving speed (see Fig. 11). The impact angle increased from 0° to 45° when the \(q_{\text{max}}\) increased from 4.51–4.69 to 5.09–5.31 MW/m\(^2\), as shown in Fig. 12, which is about 12.8%–13.2% increase. Obviously, a large forward impact angle weakened the upstream parallel flow. The precooling heat transfer effect before direct-flow impingement slowed down, and the hot plate surface maintained higher temperature.

When the jet impinges directly on the measuring point under continuous flow of cold water, the temperature difference between the liquid and the solid becomes relatively large, therefore the heat flux increases. The width of the transition boiling region \(\Delta t_{\text{MHF}} - t_{\text{w}}\) was obtained using the length time of the transition boiling \((\Delta t_{\text{MHF}} - t_{\text{w}})\) and the moving speed of the nozzle:

\[
\Delta t_{\text{MHF}} - t_{\text{w}} = \left(\Delta t_{\text{MHF}} - t_{\text{w}}\right) \times V \quad \ldots \ldots \ldots \ldots \quad (6),
\]

where \(V\) is the moving speed of the nozzle; \(t_{\text{w}}\) is rewetting delay time, which starts from impingement to rewetting point is obtained by using time varying surface heat flux curves\(^{(32)}\) as is starting point (shown in Fig. 11(a)); \(\Delta t_{\text{MHF}} - t_{\text{w}}\) is the time needed to reach the maximum heat flux starting from the beginning of the impingement to \(q_{\text{max}}\). The \(q_{\text{max}}\) position is located in the visible leading edge of the wetting zone.\(^{(33)}\) Thus, \(\Delta t_{\text{MHF}}\) can be obtained from the analyzing video images every 0.05 s. Since the variation of heat flux is divided into the beginning of the impingement to \(q_{\text{max}}\), \(\Delta t_{\text{MHF}} - t_{\text{w}}\) decreased from 1.75 to 1.64 s, but the width of \(\Delta t_{\text{MHF}} - t_{\text{w}}\) increased from 22 to 25 mm.

Figure 13 shows that as the angle increased from 0 to 45°, \(\Delta t_{\text{MHF}} - t_{\text{w}}\) decreased from 3.05 to 1.6 s (which is about 32% decrease), and the \(\Delta t_{\text{MHF}} - t_{\text{w}}\) width decreased from 15 to 25 mm. Thus, the time to reach the nucleate boiling was shortened and the width of the transition boiling region became narrower, which means that the heat transfer process transferred earlier into the nucleate boiling stage. This phenomenon can be explained by the parallel flow enhancement and the subcooling \(\Delta T_{\text{sub}}\) decrease in the downstream region during the parallel flow expansion or a larger forward-inclined angle.\(^{(34)}\)

As shown in Figs. 11(a)–11(d), the heat flux curves are almost parallel when the nozzle moves in the same direction as the impact water flow. The rewetting front line is straight. Slit nozzle direction is inclined by \(-15^\circ\). The nozzle moves in the opposite direction relative to the slit nozzle, thus, the space between the adjacent heat flux curves becomes uneven. Their paths even cross each other before they reach heat flux peak as shown in Fig. 11(e). \(q_{\text{max}}\) fluctuation ranges from 4.5 to 4.9 MW/m\(^2\), which is much larger when heat flux moves forward.

As presented in Fig. 14, the wetting front is a curve with a relatively smaller \(\Delta t_{\text{MHF}}\) at a jet angle of \(-15^\circ\). This is similar to the stationary vertical case 0°, as mentioned above. Unstable parallel flow accompanying the sputtered droplets is an inconsistent wetting process, propagating an uneven wetting front along the width of the slit nozzle. This out-of-sync phenomenon is amplified at the edge of the plate where the water flows more easily, and lowers the surface temperature of the plate, speeding up rewetting process.\(^{(34)}\)

3.2.3. Effect of Slit Nozzle Moving Speed on Jet Impinging Process

As shown in Figs. 15 and 16(a), \(q_{\text{max}}\) decreased from 4.83–4.95 to 4.55–4.66 MW/m\(^2\) at 15° impact angle and 15 L/min water flow as the nozzle moving speed decreased from 20 to 15 mm/s (as shown in Fig. 11(b)). The descending rate was \(-5.8\%\). The lower moving speed extended the impact time of the high-kinetic-energy flow and increased the maximum local Nusselt number.\(^{(31)}\) Therefore, lower moving speed produced higher heat flux. However, the \(q_{\text{max}}\) did not change significantly when the nozzle moving velocity further reduced to 10 mm/s. The rewetting delay time \(t_{\text{w}}\) and the time to reach \(q_{\text{max}}\), \(t_{\text{MHF}}\), were strongly depended on the speed of the plate movement.

As the nozzle moving velocity increased from 10 to 20 mm/s, the \(t_{\text{w}}\) time interval between two adjacent measuring points decreased significantly, indicating propagation of the rewetting front along the plate as it moved forward. \(\Delta t_{\text{MHF}} - t_{\text{w}}\) decreased slightly from 1.75 to 1.64 s, but the width of \(\Delta t_{\text{MHF}} - t_{\text{w}}\) increased from 17 to 27 mm, as shown in Fig. 16(b). Fujimoto et al.\(^{(35)}\) pointed out that the liquid/solid contact time becomes shorter and the size of the wetted area on the front side becomes narrower with increasing moving velocity. They also observed lower wall friction and drag forces between the cooling water and the boiling vapor bubbles.

4. Conclusions

The principle of slit jet impingement heat transfer was experimentally studied and the main results can be summarized as follows.

(1) Distribution of the heat transfer area when the stationary slit jet impinges on the hot plate surface was studied using cooling curves and digital images. The heat transfer characteristics (such as \(q_{\text{max}}, t_{\text{MHF}}, T_{\text{MHF}},\) and rewetting front propagation) were significantly different in the upstream and downstream regions at different inclined angles.

(2) The water flow structure and heat transfer region distribution of the moving inclined slit jet impingement cooling process were studied as well. The parallel flow and intense sputtering were obvious in the downstream region. The antiparallel flow in the upstream region was thinner, had less sputtering and was relatively stable. The small liquid accumulation region, film boiling region, transition boiling region, nucleate boiling region, and single-phase force convection region were distributed from upstream to downstream direction.

(3) Increase of the impact jet angle significantly improved the heat transfer capacity of the forward-moving inclined slit jet impingement cooling process. Higher moving speed reduced the \(q_{\text{max}}\), and promoted the location reaching \(q_{\text{max}}\) moving to the downstream region.
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Nomenclature

\[ q_s \] surface heat flux (MW/m²)
\[ q_{\text{max}} \] maximum heat flux, MHF, (MW/m²)
\[ t_{\text{MHF}} \] cooling time at the maximum heat flux (s)
\[ t_{\text{w}} \] rewetting delay time (s)
\[ T_s \] surface temperature (°C)
\[ T_{\text{rW}} \] surface temperature at the resident time (°C)
\[ T_{\text{SCT}} \] surface temperature when the location reaches its maximum heat flux (°C)
\[ U_0 \] initial velocity (m/s)
\[ U_{\text{max}} \] maximum jet centerline velocity (m/s)
\[ \alpha \] angle between the nozzle and the vertical line (°)
\[ \Delta T_{\text{sub}} \] liquid sub-cooling temperature (°C)
\[ r_{\text{MHF}} \] distance from the impinging line (mm)
\[ r_{\text{w}} \] position of the wetting front of the impinging line (mm)
\[ L \] the slit length (mm)
\[ T_{\text{SCT}} \] starting cooling temperature (°C)
\[ T_W \] water temperature (°C)
\[ H \] impingement height (mm)
\[ r_{\text{f}} \] distance from impact line (mm)
\[ V \] moving speed of the nozzle (mm/s)

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