Boiling Heat Transfer Characteristics of Vertical Water Jet Impinging on Horizontally Moving Hot Plate

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(*Received on July 6, 2017; accepted on August 23, 2017*)

This study investigates the heat transfer characteristics of a circular jet pointing upward that impinges on a moving hot steel sheet by using a laboratory-scale setup. The test liquid was water at 17°C, and the volumetric flow rate of the coolant was set to 450, 960, and 1 480 mL/min. The test solid was 0.3 mm thick stainless steel (SUS430) with an initial temperature in the range 300–700°C. The moving velocity of the solid was set to 0.5, 1.0, and 1.5 m/s, and its temperature profile was measured by an infrared camera. The results showed that a region of high heat flux appeared in the area impacted by the jet. The heat transfer characteristics relied heavily on the initial temperature of the solid associated with the boiling patterns—namely, nucleate, transition, and film boiling. Along the boundary between the strong nucleate and the transition boiling regimes, the heat flux took peak values. The local minimum values of heat flux obtained between the transition and the film boiling regimes. The initial temperatures of the solid exhibiting these values were influenced by its moving velocity and the jet impact velocity. Moreover, the heat fluxes in the jet impact region for upward-impinging jets were compared with reported data for downward-impinging jets under the condition whereby the jet impact velocity and diameter in the two cases were nearly identical prior to impact. The two sets of results showed very similar trends, although the flow motions of water varied because of the effect of gravity.

KEY WORDS: boiling heat transfer; upward-impinging jet; flow visualization.

1. Introduction

In hot rolling mills, hot steel plates are rapidly cooled by means of water jet impingement at the top and bottom of the steel surface.[1–3] The pipe laminar, curtain laminar, and spray jet cooling methods are used to precisely control the temperature histories of steel products. Practical investigations using industrial-scale cooling systems have been carried out to assess the intensity of heat transfer in the cooling process. Franco *et al.*[4] studied the heat transfer characteristics of multi-pipe laminar jet impingement on a 6.3-mm-thick moving plate using a pilot-scale test rig. The effect of nozzle configuration on the overall rate of heat extraction was investigated. Xie *et al.*[5] experimentally studied the cooling characteristics of a 60-mm-thick moving hot carbon steel plate by multi-inclined water jet impingement in an ultra-fast cooling (UFC) system currently used in the industry, and measured the average heat transfer coefficient.

Fundamental studies on pipe laminar cooling using laboratory-scale setups have also been extensively conducted to obtain the local heat transfer rate.[3] Many past studies have addressed the boiling heat transfer characteristics of impinging water jets on static hot solids,[6–15] whereas experiments involving moving hot solids have not been conducted as often. This study is concerned with the pipe laminar cooling of a moving hot solid, and hence reviews related work in the area. Some research groups have studied the quenching process of a hot rotating metal cylinder through the impingement of a subcooled planar water jet[17,18] and a circular water jet.[19,20] In the experiments, jet impingement on a moving solid occurred once per rotation of the cylinder in order to implement a multi-jet impact test. The research showed that the temperature of solid sharply decreases in the jet impact regions and some heat recovery occurs in other regions due to heat conduction in the solid. As a consequence, the temperature of the solid decreases with time with a saw-like (zig-zag) profile.

Chen *et al.*[16] investigated heat transfer between an upward-facing circular water jet and a moving or stationary 6.35-mm-thick low-carbon hot steel plate. They reported that overall cooling efficiency improved in the case of the moving plate than the stationary one. Fujimoto *et al.*[21–23] studied the hydrodynamics and the heat transfer characteristics of downward circular jets impinging on a hot moving stainless steel sheet by means of flash photography and thermography. The effects of varying jet velocity, and the moving velocity and temperature of the solid were investigated. Jha *et al.*[24] investigated the cooling process of a 6-mm-thick steel plate from 900°C to room temperature by a circular impinging jet. The effects of varying water flow rate and the speed of the plate on the cooling rate was investigated.

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DOI: http://dx.doi.org/10.2355/isijinternational.ISIJINT-2017-383

They proposed a correlation that could predict the critical heat flux(CHF) in their experiments.

An upward-facing impinging jet under a moving surface has not been studied as often as downward jets. **Figure 1** shows the schematics of the flow motion due to the impingement of upward- and downward-facing circular jets on a moving horizontal solid. In cases involving the downward jet, the water jet issues from a pipe nozzle, falls vertically downward, and makes impact with the solid surface, followed by the formation of a liquid film along the solid substrate. For an upward-impinging jet, the liquid film comes easily off the solid surface due to gravity. Such a difference in the flow motion of the liquid between upward- and downward-impinging jets can influence the heat transfer characteristics. Wang *et al.*[25] experimentally studied the transient cooling process of a static stainless steel plate by downward and upward circular jet impingement, and reported differences between the two temperature histories of the solid. Nakata *et al.*[26,27] recently studied the intensive cooling of hot moving steel at a high water flow rate. They showed that the orientation of the solid surface affects the heat transfer characteristics. However, considerably more knowledge is needed of the differences/similarities in flow and heat transfer characteristics between upward/downward jets impinging on a moving solid. This is the main motivation for this study.

The objectives of this study are to (1) understand the heat transfer characteristics of an upward-impinging jet by means of laboratory-scale experiments and (2) investigate differences/similarities in hydrodynamics and heat transfer characteristics between upward- and downward-impinging jets in the vicinity of the jet impact region by comparing the results of experiments reported here with data obtained from past work.[22] The experimental method used here was similar to that in our past work[22] for the downward jet, so that a direct comparison of the cooling characteristics of the downward- and upward-impinging jets could be conducted. The test coolant was water at 17°C and the test solid was a thin stainless steel sheet. The impact velocity of the jet, temperature of the solid and its moving velocity were systematically varied. The effects of these parameters on hydrodynamics and the heat transfer process are discussed in detail.

2. Experiments

2.1. Experimental Setup and Data Reduction Method

A schematic diagram of the experimental apparatus for observing upward-impinging jets is shown in **Fig. 2**. Cooling water at approximately 17°C was stored in a reservoir and transported by a mechanical pump to a pipe nozzle through a regulating valve and a flow meter. Three types of pipe nozzles, with inner diameters of 3, 4, and 4.5 mm, were prepared. The pipe length was 50 cm. A flow-disturbing mesh was inserted into the inlet of the nozzle to form a fully developed turbulent pipe flow near its mouth, where the water jet issued vertically upward. The nozzle-to-plate spacing was set to $H=10$ mm. The volumetric flow rate Q of water was set to 450, 960, and 1 480 mL/min.

The test sheet was made of stainless steel (SUS430), and was 60 mm wide, 220 mm long, and 0.3 mm thick. Both of the longer sides of the sheet were bent at a right angle 5 mm from the edge to prevent unwanted deformation due to thermal stress during the experiments. The test sheet was initially located at an upstream point in the test section and heated to a preset initial temperature by electrical resistance heating. The initial temperature of the solid T_S was varied from 300 to 700°C. A linear motor actuator transported the test sheet into the observation section at a preset velocity (0.5, 1.0, and 1.5 m/s). The liquid flow formed by jet impingement was observed by flash photography using a digital camera and a flashlight. The temperature profile of the moving test sheet was measured at the opposite side of the cooled surface (non-wetting surface) using an infrared camera with a resolution of 320×240 pixels. A thin coat of black body paint with an emissivity of 0.94 was added to the dry side of the test sheet to ensure accurate measurement of temperature.

The inverse heat conduction problem was numerically solved to examine the heat transfer characteristics on the wet surface. We assumed that the temperature profile inside the solid was steady in a coordinate system fixed in space. The heat conduction equation is given by

$$\rho c V_s \frac{\partial T}{\partial x} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (1)$$

where $T, V_s, \rho, c,$ and λ represent the local temperature and

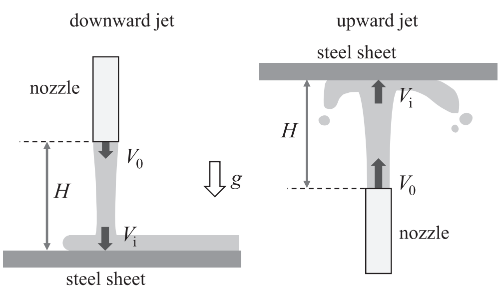

Fig. 1. Upward- and downward-impinging jets on a moving hot solid.

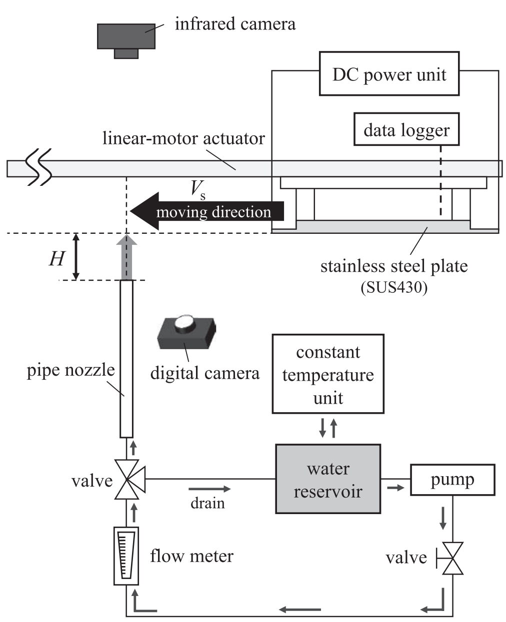

Fig. 2. Experimental apparatus.

the moving velocity of sheet, and its density, specific heat, and thermal conductivity, respectively. The coordinates (x, y, z) were in directions of the length (x), the width (y), and the thickness (z) of the sheet. The temperature dependence of the physical properties was also taken into account. The local temperature and heat flux profiles on the cooled surface were calculated by using Eq. (1) and used as boundary conditions. More information concerning the experimental method and the data reduction is provided in our previous work.[21,22]

2.2. Some Remarks on Comparing Upward-/downward-impinging Jets

The difference in flow motion between the upward and downward jets was derived from the gravitational effect. The local jet velocity in the vertical direction and the cross-section of the jet were varied along the path of the flow as shown in Fig. 1. In case of the downward jet, jet velocity increased with increasing distance to the mouth of the nozzle and decreasing cross-section. For the upward jet, jet velocity decreased upward and its cross-section increased. The jet impact velocity V_i can be given by jet velocity V_0, at the mouth of the nozzle, the nozzle-to-plate distance H, and the gravitational acceleration g though a simple energy conservation law:

$$V_i = \begin{cases} \sqrt{V_0^2 + 2gH} & \text{for downward jet} \\ \sqrt{V_0^2 - 2gH} & \text{for upward jet} \end{cases} \quad \text{............ (2)}$$

The impact diameter d_i of the circular jet was calculated by a mass conservation law using the inner diameter d_0 of the circular nozzle as

$$d_i = d_0 \sqrt{V_0 / V_i} \quad \text{............................ (3)}$$

Equation (3) suggests that the impact diameter was influenced by H and V_0.

A comparison of the results for the upward- and downward-impinging jets was carried out under the same impact velocity V_i, and jet impact diameter d_i. In our previous work,[22] the inner diameter of the pipe nozzle was d_0=5 mm and the nozzle-to-plate spacing was H=40 mm. The mean jet velocity at the nozzle exit was set to 0.4, 0.8, and 1.2 m/s. The corresponding jet impact velocity according to Eq. (1) was 0.97 m/s, 1.19 m/s, and 1.49 m/s. In order to obtain the same jet impact velocities, three types of nozzles with different inner diameters were used under a fixed nozzle-to-plate spacing of H=10 mm. We set flow conditions of (Q, d_0)=(450 mL/min, 3.0 mm), (960 mL/min, 4.0 mm), and (1 480 mL/min, 4.5 mm) so that values of V_i=0.97, 1.19, and 1.49 m/s were obtained. Note that the jet impact diameters were slightly different from those in our previous work because we could not prepare the pipe nozzles to obtain exactly the same diameters.

3. Results and Discussion

3.1. Flow and Heat Transfer Characteristics for Upward Jet Impingement

The effect of varying the initial temperature of the solid substrate on the flow and heat transfer characteristics was investigated under the following conditions: volume flow rate Q=960 mL/min of water, velocity of moving sheet V_s=1.5 m/s, inner diameter of nozzle d_0=4.0 mm, and nozzle-to-plate spacing H=10 mm. The corresponding jet impact velocity was V_i=1.19 m/s. The initial temperature T_s, of the solid was varied as a parameter. **Figure 3**(a) shows examples of the flow motion of the cooling water taken by flash photography. A circular jet issuing vertically upward from the mouth of the nozzle impinged onto the hot moving plate. At T_s=300°C, liquid film spread radially along the solid surface from the jet impact point and elongated downstream. Several droplets fell away from the rim of the liquid film due to gravity. The liquid film looked hazy or cloudy because numerous boiling vapor bubbles and minute droplets scattered the observation light. The droplets were formed because of the bursting of boiling bubbles at the liquid/solid interface. At 400°C, the droplets decrease in number. Some hazy or cloudy liquid film was observed. At 500 and 700°C, the liquid film looked transparent, indicating little presence of droplets and/or boiling bubbles. At 700°C, the stainless steel sheets were red hot, and the dark area elongated downstream from the jet impact region. Moreover, the liquid spread more widely than at 300°C. The vapor was stably formed between the film of water and the solid surface, resulting in smaller viscous wall friction.

Figure 3(b) shows the measured temperature profiles of the moving hot sheets on the non-wet surface. The range of the color key was 200°C in each image. For example, in the case where T_s=300°C, the color key ranged from 105 to 305°C. The black mark in the figure indicates the jet impact point. In all cases, a linear low-temperature zone was elongated from the jet impact point in the direction of motion of the solid. A large temperature drop from the initial temperature to the low-temperature zone was observed at T_s=300°C, where strong nucleate boiling arose near the jet impact point. The temperature drops at 400, 500, and 700°C were smaller than those at 300°C. Figure 3(c) shows the estimated heat flux distribution on the wet surface. A region of high heat flux appeared near the jet impact point, suggesting that the hot solid had been cooled to a significant extent at this point. As expected, the heat flux depended on the initial temperature of the solid. A large heat flux was observed at 300 and 400°C.

3.2. Maximum Heat Flux for Upward-impinging Jet Under Varying Experimental Conditions

Boiling phenomena can be categorized into nucleate, transition, and film boiling depending on the temperature of the solid surface. As the temperature of the solid varies significantly in the jet impact region, some boiling modes usually coexist within a small region.[1] We introduce an index called "maximum heat flux," defined as the highest heat flux value in the domain of analysis. The boiling mode at the maximum heat flux point was considered to understand the effect of varying the temperature of the solid and other parameters. Note that the point showing the "maximum heat flux" did not necessarily coincide with the center of the jet impact point.[22]

Figure 4 shows the maximum heat flux under varying experimental conditions. The data for downward jets[22] are also plotted for reference. We discuss here the results for upward jets, and the results for the downward jets are

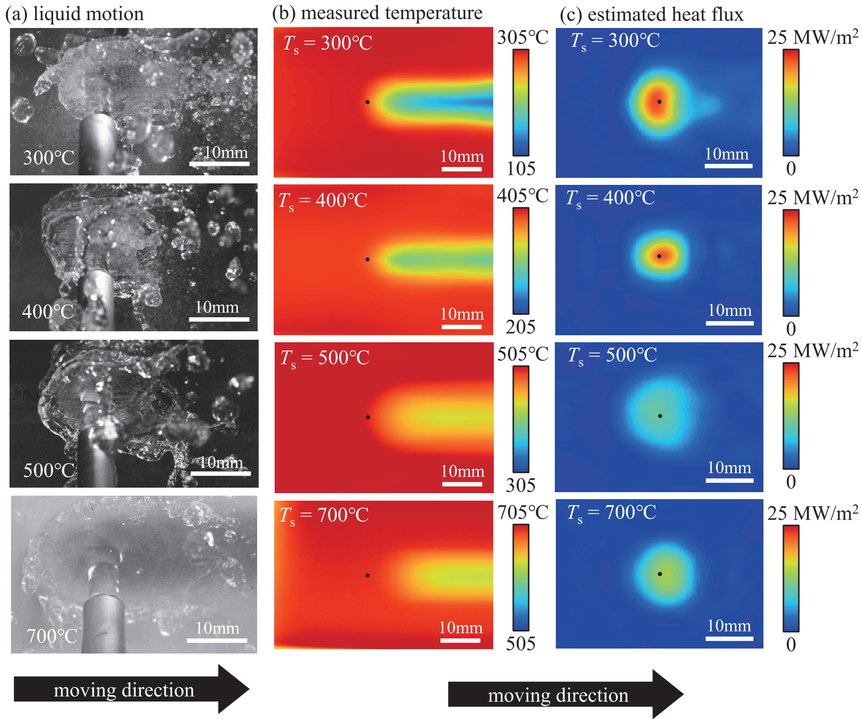

Fig. 3. Results obtained in experiments under a volume flow rate of water Q=960 mL/min and velocity of moving sheet V_s=1.5 m/s. (a) Liquid flow motion captured by flash photography. (b) Measured temperature profile. (c) Estimated heat flux distribution on the wet surface.

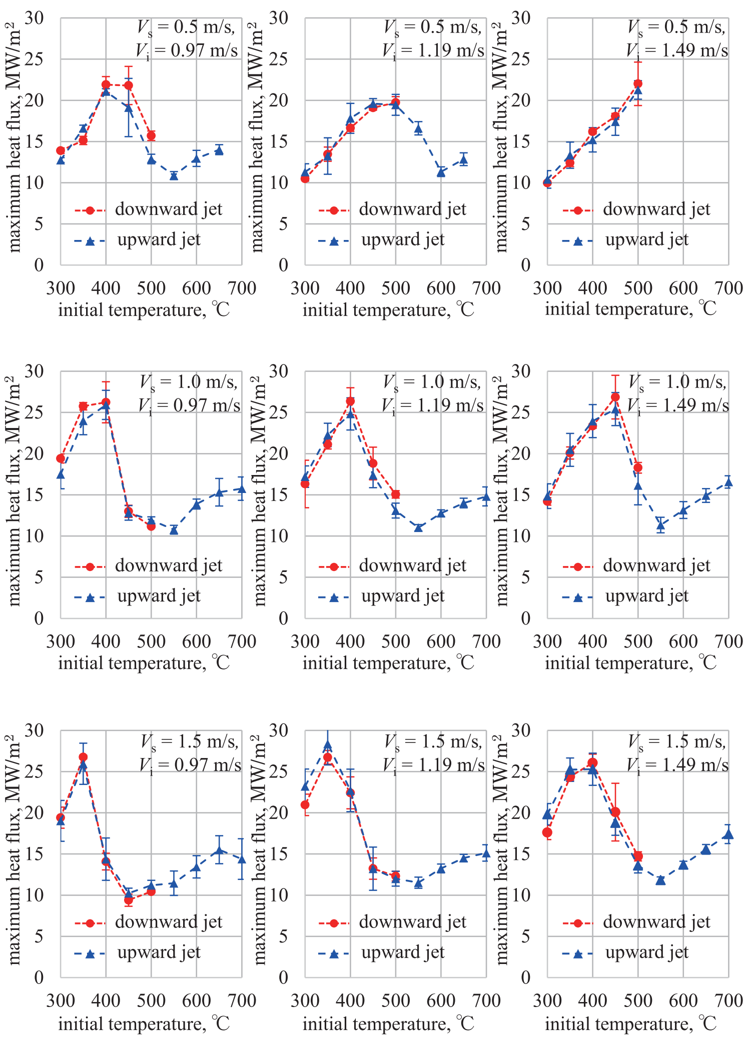

Fig. 4. Peak heat flux under various experimental conditions.

considered in the subsection 3.4. We also noted that some maximum heat fluxes at temperatures higher than 500°C were missing for v_i=1.49 m/s and v_s=0.5 m/s because undesirable deformation of the test solid sheet occurred due to thermal stress upon jet impingement.

In most cases, the maximum heat flux for the upward jets increased with the initial temperature of the solid, assumed a peak, decreased, reached a valley value, and increased again. The peak and valley values are often referred to as CHF (critical heat flux) and MHF (minimum heat flux), respectively. The boiling mode was nucleate boiling in the region below the CHF point. Transition boiling appeared in the range between the CHF and MHF points, and film boiling was observed above the MHF. Accurate measurement of the CHF and MHF points was beyond the scope of this study, but we observed trends whereby the initial temperatures of the solid exhibiting CHF increased for large jet impact velocities or smaller sheet velocities. The MHF points were also affected by these parameters. As the boiling mode is primarily influenced by the local temperature of the solid surface, such a temperature shift occurred because of the difference between the initial and local temperatures of the solid.

The effect of jet velocity on temperature shift can be easily explained. A large inertial impact of the water jet enhanced the heat transfer rate and led to a large difference between the initial and local surface temperatures. As a consequence, a large temperature shift occurred in the CHF point.

In order to explain the effect of varying the velocity of the solid on temperature shift, an ideal model was built. **Figure 5** shows a rectangular control volume in the jet impact region with dimensions L, dy, and δ along the x-, y-, and z-directions, respectively. δ was the thickness of the sheet. We assumed that the heat $qLdy$ was removed from the wet surface per unit time in the jet impact region, where q is the average heat flux. The heat $\rho c V_s T_1 \delta dy$ entered into the control volume per unit time through the upstream boundary due to solid motion, where T_1 is the average temperature of the solid along the upstream boundary. Moreover, the heat $\rho c V_s T_2 \delta dy$ exited through the downstream boundary. We assume that heat transfers due to heat conduction at the boundaries of the control volume and heat removal at those of the dry surface were negligibly small compared to the above values. A simple energy conservation law yields the following equation:

$$\frac{T_1 - T_2}{L} = \frac{q}{\rho c V_s \delta} \quad \text{(4)}$$

The above equation shows that a slower moving velocity of the solid induced greater temperature drops when q was constant. Although heat flux q varied according to the moving velocity of the solid in situations involving cooling, the experimental results can be roughly explained by the equation. The local temperature of the solid surface was lower for smaller sheet velocities, suggesting that the higher initial temperature was needed to show a CHF. As a result, the initial temperatures of the solid exhibited a CHF shift to the higher side, as shown in Fig. 4.

3.3. Comparison between Our Experimental Data and Chen *et al.*'s Results

Chen *et al.*[16] investigated heat transfer between an upward circular water jet and a moving, 6.35-mm-thick low-carbon hot steel plate. We conducted an experiment under similar experimental conditions to those used by Chen *et al.* **Figure 6** shows a comparison between the surface temperature measured by Chen *et al.* and our result along a direction of motion passing through the jet impact point under the following conditions: an initial solid temperature of 240°C, a moving velocity of the solid of 0.5 m/s, and a jet impact velocity of 2.3 m/s. Note that there were some differences in experimental conditions between our and Chen *et al.*'s work, including plate thickness, nozzle diameter, and the method to measure the temperature of the solid. They measured the temperature history of the solid surface using K-type surface-mounted thermocouples with a wire diameter of 0.00127 mm and a sampling time of 1 ms. The thermocouples were transported with the solid. Immediately after the cooling water directly contacted the thermocouples, the measured drop in temperature increased abruptly. As they had not specified the exact location of the jet impact point, the position at which the temperature drop began was set as reference point for comparison. The surface temperatures significantly declined from 240 to approximately 70°C. Thereafter, some heat recovery occurred in Chen *et al.*'s experiment due to heat conduction in the solid. On the other hand, heat recovery rarely occurred in our experiment because the heat capacity of the thin solid sheet was very small.

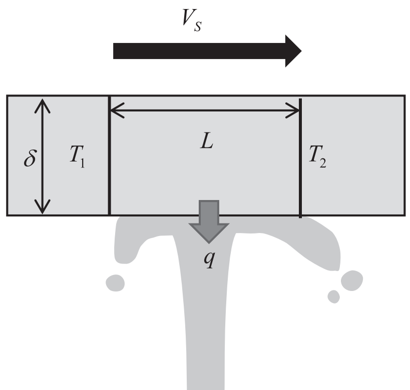

Fig. 5. Simple heat model.

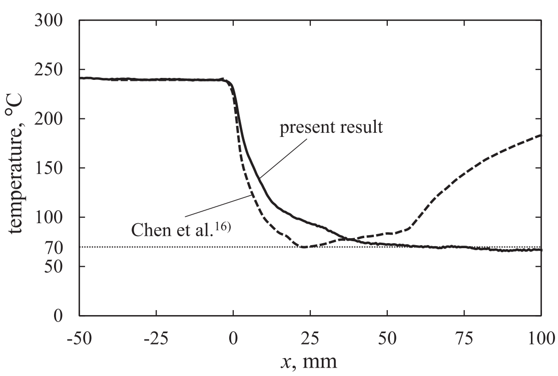

Fig. 6. Comparison between the results of this study with those of Chen *et al.*

Chen *et al.*'s results showed a higher temperature gradient just downstream of the reference point than ours. This was due to the difference in temperature measurement methods between the two experiments. In our experiment, temperature measurement was conducted at the opposite surface by means of an infrared camera fixed in space with an exposure time of 1/60 s. The measured temperature profile was time-averaged and the temporal fluctuation in temperature was minimized. Nevertheless, our experimental data agreed moderately with those of Chen *et al.*

3.4. Comparison in Terms of Heat Transfer Characteristics between Upward and Downward Jets

We compared our results here with those of our previous experiments[22] to investigate the differences/similarities between upward- and downward-impinging jets in terms of hydrodynamics and heat transfer characteristics. The comparison was conducted at a temperature range of 300–500°C for the solid. As previously explained, significant hydrodynamic differences between the upward- and downward-impinging jets arose due to gravity. The residual liquid was rarely found on the moving solid surface for the upward jet as shown in Fig. 3. As a consequence, the local temperature of the solid surface, in a region sufficiently downstream from the jet impact point, became slightly higher than that for the downward jet in all cases, although this is not shown.

Nakata *et al.*[26,27] recently studied the cooling of hot moving steel using intensive cooling at high water flow rate. They reported that the temperature drop in the steel plate for a downward-impinging jet was greater than that for the upward jet because of the presence of the residual liquid. Although their experimental conditions were very different from the ones used here, our results are consistent with their data.

Figure 4 shows that the peak heat fluxes for the upward and downward jets were very similar, suggesting little influence of the direction of flow on heat transfer characteristics in the jet impact region. As previously stated, the jet velocity and diameter just prior to impact were carefully adjusted to compare the results of the upward and downward jets, with the result that the two flow structures were hydrodynamically similar in the jet impact region. The resultant temperature profiles of the liquid and solid were similar as well. Thus, the results in Fig. 4 are reasonable.

Downward-impinging jets have been extensively studied through experiments whereas scant work has been done on upward-impinging jets. The results of this study indicate that experimental data for downward-impinging jets are applicable to the jet impact regions to some extent in predicting their heat transfer characteristics. This finding is quite useful from an engineering perspective.

4. Conclusions

This study experimentally investigated the cooling characteristics of a moving hot plate due to the impingement of an upward jet. Our findings can be summarized as follows:

(1) The hydrodynamics and the heat transfer characteristics of the upward water jet impinging on a moving hot solid were investigated by varying the initial temperature of the solid, the jet impact velocity, and the moving velocity of the solid. A low-temperature region of the solid elongated from the jet impact point, and a region of high heat flux was observed in the jet impact region.

(2) The maximal heat flux increased with the initial temperature of the solid, and reached a peak, decreased, assumed a valley value, and increased again. The initial temperatures of the solid showing CHF and MHF were influenced by jet impact velocity and the moving velocity of the solid.

(3) The peak heat fluxes for the upward- and downward-impinging jets were compared under the conditions of identical jet impact velocity and cross-section of jet at the solid surface. The two results agreed reasonably well, which suggests that experimental data for downward impinging jets are applicable, to some extent, to predict the heat transfer characteristics of upward-impinging jets.

Acknowledgment

This work was supported by the 24th Research Promotion Grant from the Iron and Steel Institute of Japan.

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