Jet Impingement Quenching: Effect of Coolant Accumulation

Nitin Karwa¹, Peter Stephan²
Institute of Technical Thermodynamics, Center of Smart Interfaces, Technische Universität Darmstadt, Petersenstraße 32, 64287 Darmstadt, Germany
E-mail: ¹karwa@ttt.tu-darmstadt.de
E-mail: ²pstephan@ttt.tu-darmstadt.de

Abstract. During quenching of wide steel plates with impinging water jets in the accelerated cooling section of a plate mill, the coolant accumulates over the plate. In this study, the effect of coolant accumulation on the heat transfer rate during jet impingement quenching has been investigated. In these experiments, the coolant accumulates over the impingement surface of the test specimen within a volume created by assembling a ceramic tube length around the test specimen. The quenching rate with and without the accumulation of coolant are compared. The propagation of the wetting front is decelerated due to the accumulation of coolant. The reduction in the jet impingement momentum as it passes through the accumulated layer of coolant and the obstruction to the radial outflow of the released vapor by the ceramic tube are the likely reasons for this observation. The maximum heat flux value, analogous to the critical heat flux condition of steady state pool boiling, decreases due to accumulation, but the corresponding temperature shows little dependence on accumulation. This study contributes to further the understanding of the jet impingement quenching process.

1. Introduction
Rapid cooling of steel plates, with temperature as high as 800-1000 °C, by impinging liquid jets is a widely accepted technique in the accelerated cooling section of a plate mill. A schematic of the jet impingement condition on the top and the bottom face of a stationary wide plate is shown in Fig. 1. Typical water mass flux can be up to about 20 kg·m⁻²·s⁻¹ [1], which leads to accumulation of the coolant over the top surface of the plate. The retained water height can be up to 200 mm for large plates [1–3]. The flow on the top surface before accumulation of the coolant and on the bottom face can be classified as free-surface jet impingement, while the flow after accumulation can be classified as a plunging jet impingement. Furthermore, the plate moves through the cooling section, which has considerable effect on the cooling rate [4]; however,
this effect has not been investigated in the present study. The parts may get distorted due to thermal stresses induced by non-homogeneous cooling; therefore, it is important to understand the effect of coolant accumulation on the quenching rate. While free-surface jet impingement quenching studies of a stationary plate has been reported previously [5–12], the effect of coolant accumulation has not been reported. The aim of this work is to study plunging jet impingement quenching of a stationary steel plate with thermal conditions comparable to that in a plate mill.

2. The experimental set-up
A schematic of the experimental set-up is shown in Fig. 2. The main components of the set-up are the flow loop, test section and data acquisition system (DAQ). A schematic of the test section is also shown. In the test section, a cylindrical stainless steel test specimen enclosed in a test cell is quenched by a normally impinging coaxial jet. The coolant (deionized water)

![Figure 2. A schematic of the setup showing the flow loop, test section and DAQ system. The test section consists of the test cell, jet nozzle and cameras.](image)

from the reservoir is pumped by the gear pump and the flow rate is set by regulating the pump speed. The three-way solenoid valve continuously returns the liquid back to the reservoir until it is triggered to route the liquid to the jet nozzle. The jet nozzle has a pipe-type design with an internal diameter \(d_N = 3 \text{ mm}\) and length of 288 mm. Any trapped air inside the liquid line is purged out through an air vent installed just before the nozzle inlet. During quenching, two cameras (one high-speed camera and one low-speed camera) capture the process, while a 18-bit NI SCXI data acquisition system acquires the temperature and flow rate data at 100 Hz.

Figure 3 shows the test specimen assembled within the test cell. The cylindrical test specimen, 50 mm diameter and 20 mm height, is made from stainless steel AISI-type 314. The thermal properties of stainless steel AISI-type 314 are compiled in Table 1. The average roughness of the top surface has been determined to be 0.2 \(\mu\text{m}\). Thirteen holes of 0.5 mm diameter are drilled using electrical discharge machining process from the bottom surface of the test specimen to a depth of 19.4 ± 0.05 mm. The holes are located along a radial line and are spaced 2 mm apart. The thermocouples are fixed inside these holes. The side and the bottom of the test specimen are thermally insulated, while heat transfer takes place from the top surface.

Type-K class 1 grounded thermocouples encased in a stainless steel AISI-type 314 sheath, 0.5 mm in diameter, are fixed inside the holes in the test specimen. The thermocouples have been calibrated with an accuracy of ±1 K over the temperature range of 200–1000 °C. For the range of calibration, the noise in the temperature measurement is 3\(\sigma = 0.33\) K and the overall measurement accuracy is 1.45 K. In order to minimize thermal contact resistance between the dead end of the hole in the test specimen and the thermocouple, a high temperature thermal conductive paste has been filled inside the hole before pushing the thermocouple to the hole end.
The thermocouples have been reinforced in place at the bottom face of the test specimen using a metallic adhesive. With this arrangement, the thermocouple tip must be at a depth of 0.6 mm from the impingement surface and the thermocouple junction is geometrically determined to be at a depth of 0.85 mm.

| $T$ [$^\circ$C] | $\lambda_T$ [W·m$^{-1}$·K$^{-1}$] | $c_T$ [J·kg$^{-1}$·K$^{-1}$] | $\rho_T$ [kg·m$^{-3}$] | $\alpha_T$ [m$^2$·s$^{-1}$] |
|----------------|---------------------------------|-----------------------------|-------------------------|--------------------------|
| 300            | 17.2                            | 556.6                       | 7689                    | 4.014·10$^{-6}$          |
| 600            | 21.9                            | 638                         | 7561                    | 4.542·10$^{-6}$          |
| 900            | 26.7                            | 749.3                       | 7433                    | 4.794·10$^{-6}$          |

The coolant accumulates inside an accumulation volume that is created by assembling a low conductivity ceramic cylinder of height $h_p$ on top of the test cell. A steel disc is shrink fitted around the ceramic cylinder in order to improve its thermal shock resistance. In order to avoid any leakage of the accumulated liquid, the ceramic cylinder is pressed down on to a retaining ring and is reinforced into position using a ceramic cement. Additionally, a 2 mm thick mica sheet covers the top of the test cell outside the ceramic accumulation cylinder. A snapshot of the test section with a ceramic cylinder of $h_p = 30$ mm assembled on top of the test cell is shown in Fig. 4. The test specimen is induction heated to the desired temperature, after which the jet is allowed to impinge on the impingement surface. As the cooling progresses, the coolant fills up the accumulation volume. Once the accumulation volume is completely filled, the liquid spills over the edge of the ceramic cylinder.

The experiments have been carried out for a fixed nozzle diameter and nozzle-to-surface spacing of 3 mm and 97.5 mm, respectively. The jet impingement velocity $v_J$ is 2.5 m·s$^{-1}$ and 5 m·s$^{-1}$. The initial temperature of the test specimen is fixed within 880–900 $^\circ$C. The experimental conditions are given in Table 2. The effect of accumulated liquid in the plunging jet impingement quenching on the surface heat flux and temperature is compared with that of free-surface jet impingement quenching. Free-surface jet impingement experiment F1 is comparable to plunging jet experiments P1 and P2, as the jet velocity and subcooling are the same among the three experiments, i.e. 5 m·s$^{-1}$ and 75 K, respectively. The accumulation heights in experiments P1 and P2 are 30 and 80 mm, respectively. Based on the mass flow rate of the jet, the filling time in experiments P1 and P2 are calculated to be 1.7 s and 4.5 s, respectively.
Figure 4. Snapshot of the test section with a ceramic cylinder of \( h_p = 30 \text{ mm} \) (1: jet nozzle, 2: impingement surface, 3: Ceramic cylinder with a shrunk stainless steel disc, 4: ceramic cement, 5: mica sheet, 6: high speed camera, 7: mirror).

Experiment P3 can be compared to experiment F2, as the jet velocity and subcooling of 10 m·s\(^{-1}\) and 75 K, respectively, are the same among both the experiments. The accumulation height in experiment P3 is 80 mm and the filling time is 2.3 s.

### Table 2. Experimental conditions.

|   | \( T_I \) [°C] | \( T_L \) [°C] | \( v_J \) [m·s\(^{-1}\)] | \( \dot{m}_J \) [kg·m\(^{-2}\)·s\(^{-1}\)] | \( h_p \) [mm] | filling time [s] |
|---|---|---|---|---|---|---|
| F1 | 895 | 25.9 | 5.1 | 17.67 | 0 | 0 |
| P1 | 890 | 25.0 | 5 | 17.5 | 30 | 1.7 |
| P2 | 881 | 25.0 | 5 | 17.5 | 80 | 4.5 |
| F2 | 895 | 25.3 | 9.8 | 34.8 | 0 | 0 |
| P3 | 893 | 25.9 | 10 | 35 | 80 | 2.3 |

### 3. Analysis of experimental data: inverse heat conduction analysis

In order to estimate the spatiotemporal variation of the wall heat transfer boundary condition, inverse heat conduction analysis has been performed in Inverse2D using the measured temperature data from the embedded thermocouples and with the assumption of constant thermal properties that are calculated at 600 °C. The details of the model are given in Woodfield et al. [13]. The limitations of the analysis are summarized by Karwa et al. [6].

### 4. Results and discussion

A snapshot of a typical free-surface jet impingement process is shown in Fig. 5. Soon after the commencement of cooling, a wetted region is formed. It grows in size as the cooling progresses. In the estimated heat flux and surface distribution, it can be seen that the heat transfer rate is high within the wetted region and the surface temperature is lower as compared to the region outside it. Figure 6 shows a typical estimated cooling curve for \( r = 20 \text{ mm} \) in experiment F2. With the change in the slope of the curve, various regimes can be identified.

Figure 7(a) compares the variation of surface temperature with time for plunging jet experiments P1 \((v_J = 5 \text{ m·s}^{-1} \text{ and } h_p = 30 \text{ mm})\) and P2 \((v_J = 5 \text{ m·s}^{-1} \text{ and } h_p = 80 \text{ mm})\) with the free-surface jet experiment F1 \((v_J = 5 \text{ m·s}^{-1} \text{ and } h_p = 0 \text{ mm})\). In general, the growth of the high heat transfer region, i.e. the wetted region, is slightly slowed down due to accumulation. The radial distribution of surface temperature is almost similar in the three experiments during the early stages of quenching, i.e. when the accumulated liquid height is small, but with time the cooling starts to lag behind in the plunging jet experiments as the accumulated liquid height increases. Comparison of experiments P1 \((v_J = 5 \text{ m·s}^{-1} \text{ and } h_p = 30 \text{ mm})\) and P2 shows that the radial surface temperature distribution is similar up to \( t = 1.7 \text{ s} \) (i.e filling time in experiment P1). Following this, due to the further increase in the height of accumulated coolant
in experiment P2, the cooling starts to lag behind experiment P1. The temperature histories at selected radial positions within the radial flow regions are shown in Fig. 7(b), where it can be seen that the effect of accumulation is most prominent at radial positions much away from the impingement region. Comparing the cooling curves for \( r = 16 \) mm, it can be seen that the film boiling duration is 2 s for the free-surface jet, which increases to 3.5 s and 7.25 s for accumulation height of 30 and 80 mm, respectively. Due to accumulation, the transition boiling period also reduces for this radial position. Similar observations regarding the influence of liquid accumulation can be made in the heat flux variations shown in Fig. 8. The reduction in the jet impingement momentum as it passes through the accumulated layer of coolant and the obstruction to the radial outflow of the released vapor by the ceramic tube are the likely reasons for this observation.

The variation of maximum heat flux condition, \( q_{s,MHF} \) and \( T_{s,MHF} \), with radial position and accumulation is shown in Fig. 9. Both \( q_{s,MHF} \) and \( T_{s,MHF} \) reduce with distance from the stagnation point. The decrease in liquid velocity and subcooling as it travels radially outwards reduces its cooling capacity and the heat transfer performs degrades. \( q_{s,MHF} \) reduces due to accumulation, though \( T_{s,MHF} \) shows little dependence on the accumulation. Interesting to note here is that the coolant accumulation has little affect beyond \( r/d_N \approx 4 \). The liquid that is deflected away from the impingement surface at the wetting front position splashes onto the ceramic tube and a part of it may rebound back onto the impingement surface. Most likely, beyond \( r/d_N \approx 4 \), additional heat transfer to droplets rebounding from the ceramic
Figure 7. Effect of coolant accumulation on the surface temperature when $v_J = 5 \text{ m·s}^{-1}$.

Figure 8. Effect of coolant accumulation on the heat flux when $v_J = 5 \text{ m·s}^{-1}$.
tube compensates for the deterioration in cooling performance due to coolant accumulation. The comparison of the maximum heat flux condition for the plunging jet experiment P3 and free-surface jet experiment F2 are shown in Fig. 10. Similar to the effect of accumulation in experiments with $v_J = 5 \text{ m} \cdot \text{s}^{-1}$, $q_{s,MHF}$ reduces due to accumulation. Likewise, $T_{s,MHF}$ shows no dependence on accumulation.

![Figure 9](image-url)  
(a) $q_{s,MHF}(r)$  
(b) $T_{s,MHF}(r)$  

**Figure 9.** Comparison of the maximum heat flux condition, $q_{s,MHF}(r)$ and $T_{s,MHF}(r)$, for the plunging jet and free-surface jet impingement quenching experiments with $v_J = 5 \text{ m} \cdot \text{s}^{-1}$. While the deterioration of maximum heat flux, $q_{s,MHF}$, due to accumulation can be seen, no such effect on the temperature at maximum heat flux is seen.

![Figure 10](image-url)  
(a) $q_{s,MHF}(r)$  
(b) $T_{s,MHF}(r)$  

**Figure 10.** Comparison of the maximum heat flux condition, $q_{s,MHF}(r)$ and $T_{s,MHF}(r)$, for the plunging jet and free-surface jet impingement quenching experiments with $v_J = 10 \text{ m} \cdot \text{s}^{-1}$.

5. Conclusions

The paper presents the outcome of studies carried out to understand the effect of coolant accumulation during the quenching of hot stainless steel plate, heated homogeneously to an
initial temperature of about 900 °C. It has been determined that the spread of the wetted region is retarded due to accumulation. The maximum heat flux around the jet impingement region reduces due to accumulation, however the coolant accumulation has little affect beyond $r/d_N \approx 4$. The temperature at maximum heat flux also remains unaffected by the coolant accumulation. The deceleration of the jet as it passes through the coolant leads to reduction in the heat transfer rate in and around the impingement region, outside which the heat transfer is improved by the coolant rebounding from the containing walls.

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7. Nomenclature
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\begin{align*}
d_N & \quad \text{jet diameter at the jet nozzle exit, m} \\
g & \quad \text{gravitational acceleration, m} \cdot \text{s}^{-2} \\
h_p & \quad \text{maximum height of accumulated coolant, m} \\
m_J & \quad \text{jet mass flow rate, kg} \cdot \text{s}^{-1} \\
m_{\dot{J}} & \quad \text{jet mass flux} = m_J/(\pi \cdot R^2), \text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \\
q_s & \quad \text{heat flux on the impingement surface, W} \cdot \text{m}^{-2} \\
q_{s,MHF} & \quad \text{maximum heat flux on the impingement surface, W} \cdot \text{m}^{-2} \\
r & \quad \text{radial coordinate of the test specimen, m} \\
R & \quad \text{radius of the test specimen, m} \\
S & \quad \text{spacing between jet nozzle exit and impingement surface, m} \\
t & \quad \text{time, s} \\
T_l & \quad \text{initial temperature of the test specimen, °C} \\
T_{L_J} & \quad \text{jet temperature at the jet nozzle exit, °C} \\
T_s & \quad \text{temperature of the impingement surface, °C} \\
T_{s,MHF} & \quad \text{temperature at maximum heat flux, °C} \\
T_{sat} & \quad \text{saturation temperature, °C} \\
v_J & \quad \text{jet velocity at impingement surface position} = (v_N^2 + 2 \cdot g \cdot S), \text{m} \cdot \text{s}^{-1} \\
v_N & \quad \text{jet velocity at the jet nozzle exit} = m_J/(\rho_L \cdot \pi \cdot d_N^2/4), \text{m} \cdot \text{s}^{-1} \\
\Delta T_{sup} & \quad \text{surface superheat} = (T_s - T_{sat}), \text{K} \\
\rho_L & \quad \text{density of liquid, kg} \cdot \text{m}^{-3}
\end{align*}
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