Experimental Study on Local Heat Transfer during Quenching Process by Slot Nozzles

Peng Jiang* and Licheng Wu

School of Energy and Power Engineering, Jiangsu University, Zhenjiang, China

*Corresponding author email: jiangpeng@ujs.edu.cn

Abstract. Quenching is widely used in industrial applications. The heat is transferred from the ingots by spray or jet cooling at the secondary cooling zone. In this research work, the effort is focused on the influence of jet inclination on heat transfer in the boiling process, as well as the influence of heat transfer rate by changing the jet velocity through experimental work using Nicrofer sample under 850 °C. Different angles of the jet (25°, 45°, 65°, 90°) and flow velocities (3.5 m/s, 4.8 m/s, 7.8 m/s, 12.0 m/s) were arranged in these experiments respectively. The results indicated that due to the strong cooling effect of jet quenching the Leidenfrost point was not captured. Both the jet angle and jet velocity played important roles in promoting the cooling process. The smaller the jet angle, the faster the quenching rate. The angle of 25° presented the most optimum cooling effect. The higher the jet velocity, the shorter the cooling time. For the maximum jet velocity in this experiment \( v = 12.0 \text{ m/s} \), DNB-temperature even was not identified.

Keywords: Jet cooling; Quenching; Slot nozzle.

1. Introduction
Quenching is encountered in many industrial processes such as metallurgy, microelectronics, chemical and nuclear application. It is a cooling technique, which exploits heat from hot solid by impinging coolant on the high temperature surface. It is frequently researched to increase the efficiency of the heat transfer rate, save power dissipation and reduce cost for the manufactures. Moreover, the rate of heat removal during the cooling process has a significant influence on hardness, strength, and the occurrence of residual stresses during metal processing. Improper cooling can cause insufficient aging, war page, non-uniformity of properties, and surface fracture. Consequently, after improper quenching, a costly post treatment consisting of additional heat treatment and manual straightening of warped shapes is required to meet product specifications. This post treatment is often the result of poor control over the quenching process, and may result in a large cost penalty for the metal forming operation and consumer. Therefore, it is essential to have a comprehensive understanding of the quenching process to optimize the cooling rate for a particular shape and material [1-4].

There are two main ways in quenching process: spray cooling and jet impingement. Compared with spray cooling, jet flows along the surface at a uniform speed under film cooling condition, which has higher cooling rate and causes less distortion. It can be used in many high temperature manufacturing processes, such as continuous casting, extrusion and forging. Because jet impingement is very attractive in heat transfer characteristics, many researchers have conducted a lot of experimental studies on how to effectively control the thermal behavior of jet impingement [5-7]. Jet impingement can be divided into five types: free surface jet, plunging, submerged, closed jet and wall jet. Free surface jet is the most widely used method, by injecting liquid into immiscible atmosphere and directly hitting the surface. Two main jet configurations are related to the application of free surface jet.
impingement: circular jet and slot jet, and their flow and heat transfer mechanisms are significantly different. A lot of research on heat and mass transfer of circular impinging jet have been published. The research of slot nozzle is less, although it has more beneficial functions, such as higher cooling efficiency, greater uniformity and easier control. Slot jet has more potential to obtain higher heat flux. The normal impingement with constant jet angle is generally used for jet impingement. However, the study of varying the jet impingement angle on the surface heat transfer is relatively less. This may reflect the wider application of normal impingement. However, jet impingement angle appears in many applications such as aluminum quenching [8], so it is very important to understand the heat transfer characteristics in impingement process caused by asymmetric geometry. In this experimental work, four different incident angles 25°, 45°, 65° and 90° were applied to study the effect of jet angle on jet impingement process.

Another important property of jet impingement investigated in many research works is jet velocity. The high velocity liquid jet can break through the bubble layer, enhance the solid-liquid contact, and greatly raise the critical heat flux. Therefore, among all kinds of steady-state heat transfer forms, high-velocity impingement of liquid jet is the most effective way to improve the maximum heat flux [9-11].

In this research work, the effort was mainly focused on the influence of jet inclination and fluid velocity in the quenching process. First of all, the jet cooling performance from applying different jet angles was measured quantitatively. Secondly, the heat transfer characteristic on the cooling process was determined by changing the jet velocity. The data obtained were then used to define the influence of jet angle and impingement velocity of slot nozzle quantitatively.

2. Experimental Facility

The setup of this experiment is shown in Fig. 1. An electrically heated furnace, an Infrared (IR) camera FLIR SC3000, a water tank, a computer, a centrifugal pump and a slot jet were constructed for quenching experimental work. The jet with outlet area of the slot of 50 mm×2 mm was used and metal samples were made of Nicrofer.

In this experiment, the works were repeated with different jet angles under different jet velocities by using Nicrofer. When the metal heated up inside electrical furnace reached 850 ℃, the metal sample was taken out and shifted to the right position for quenching process at which the pump was started to deliver the jet cooling under the appropriate setting. In the meantime, the data acquisition unit was also activated to record the temperature history during quenching process. The obtained datum captured by IR camera was saved in computer for further analysis. The IR camera was influenced by the emissivity of the rear surface of the rectangular sheet and the distance between the lens and the surface of the sample. Before each experiment, all the experimental instruments need to be calibrated before the experiments.

![Figure 1. Experimental facility.](image-url)
Energy input in the system minus energy output equals to the energy stored in the system [12-15]. Heat transfer mechanism is demonstrated in Fig. 2. A small volume with the width of $dz$ was controlled to investigate thermal flux transfer inside the metal. Heat transfer in the $x$ direction can be neglected, since the thickness of the sheet is very small. Therefore, only heat conduction in $z$ direction and heat convection with water flow were considered.

Figure 2. Heat transfer analysis.

In a stationary, time invariant volume $V$, the energy balance equation is as follows:

$$\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} - \dot{Q}_c = \frac{dH}{dt}$$

(1)

$\dot{Q}_{\text{in}}$: Conductive heat flow rate $[J/s]$
$\dot{Q}_{\text{out}}$: Convective heat loss resulting from water flow $[J/s]$
$\frac{dH}{dt}$: Accumulated enthalpy change $[J/s]$

According to Fourier law, heat transfer rate by conduction can be calculated as follows

$$\dot{Q}_c = B \cdot S \cdot \dot{q}_c = B \cdot S \left( -k \frac{\partial T}{\partial z} \right)$$

(2)

where $B$ and $S$ are the width and thickness of the rectangular sheet respectively. $\dot{q}_c$ is heat flux and $k$ is defined as thermal conductivity.

So, convective heat transfer of inflows and outflows in the controlled volume is represented as follows:

$$\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} = -\frac{\partial}{\partial z} \left( B \cdot S \left( -k \frac{\partial T}{\partial z} \right) \right) dz$$

(3)

Heat loss from the rectangular sheet by convection can be represented as follows

$$\dot{Q}_c = B \cdot dz \cdot \dot{q}_c$$

(4)

Where $\dot{q}_c = \alpha(T_s - T_w)$, $\alpha$ means heat transfer coefficient, $T_s$ defined as surface temperature of rectangular sheet and $T_w$ represents the water temperature.

Enthalpy change is calculated by

$$\frac{dH}{dt} = \rho c_p \left( B \cdot S \cdot dz \right) \frac{dT}{dt}$$

(5)

Where $\rho$ is the density of material, $c_p$ represents the specific heat capacity of the material.

By substituting all these equations (3), (4) and (5) into (1) will yield:

$$-\frac{\partial}{\partial z} \left( B \cdot S \left( -k \frac{\partial T}{\partial z} \right) \right) dz - B \cdot dz \cdot \alpha(T_s - T_w) = \rho c_p (B \cdot S \cdot dz) \frac{dT}{dt}$$

(6)
\[
\alpha(T_e - T_w) = k \cdot \frac{dT}{dz} - \rho \cdot S \cdot c_p \cdot \frac{dT}{dz}
\]  

(7)

3.2. Leidenfrost temperature and departure from nucleate boiling (DNB) temperature

There are two important temperatures during the cooling process, Leidenfrost temperature and DNB temperature. According to the investigation by Filipovic et al. [16] and Khalid et al. [17], the Leidenfrost point (LFP) is the position where the temperature of a hot surface starts the Leidenfrost effect. Leidenfrost temperature is calculated by the finite difference equation:

\[
\frac{dT}{dx} = \frac{T_{cc} - 2T_e + T_{wh}}{\Delta x^2}
\]

(8)

From the calculation, Leidenfrost point can be approached through the minimum value of the second derivative of the temperature profile versus position. DNB exists if boiling curve has a max peak as shown clearly in Fig. 3.

All the experiments were performed in triplicates. In this paper, one of the three batches of representative results has been presented.

Figure 3. Method to determine Leidenfrost point and DNB point.

4. Results and Discussion

4.1. Influence of Different Jet Incidence Angles on Jet Cooling

The trend of these 4 cases seemed irregular as shown in Fig. 4. This phenomenon might be caused by two reasons. One reason is the jet splash in the case of high incidence angle especially for 90°. It makes the cooling process discontinuous, although the cooling rate increases a little bit. Another reason is the inevitable deformation of sheet metal in the experiment. The larger the jet angle is, the greater the backward bending of the sheet is. This figure also showed that the change of jet angle did not have significant influence on the value of DNB temperature. However, the starting position of DNB temperature occurred earlier from the shooting point by increase of incident angle of the jet. It implied DNB temperature first occurred when the angle is 90°.

Figure 4. DNB temperature profiles over position for different jet angles.
At the shooting point, neither film boiling nor transition boiling was found, which indicated that the jet with 4.8 m/s was strong enough to inhibit formation of a vapor barrier as shown in Fig. 5(a). Moreover, bubbles of water vapor broke off and flowed in the water film and eventually escaped from the free surface. The results show that the trend of each line in the figure was the same, the heat flux decreased with the decrease of surface temperature. In this case, the heat flux at the shooting point (x = 0 mm) was independent of the influence of the incident angle, but only changed with the surface temperature.

Compared with the shooting point, the boiling curve of x=40 mm had obvious transition boiling process. All the lines in the Fig. 5(b) exhibited the same trend in the transition area: as the surface temperature decreased, the surface heat flux increased until it reached the maximum. After that, the bubbles nucleation begined on the bubble surface, the heat flux decreased with the decrease of the surface temperature, and finally reached a lower heat flux when the surface temperature was lower than 100 °C. In addition, it was found that it took a long time for a larger angle to reach the maximum heat flux from the transition point. This indicated that the mass flow rate of the jet with a smaller angle was more effective for the heat transfer in the transition region.

4.2. Influence by Jet Velocity on Jet Cooling
When water velocity reached 12.0 m/s, quenching was carried out without transition boiling. Therefore, there was no DNB temperature in Fig. 6. The same situation was for v=7.8 m/s. As shown in Fig. 6, there were only two lines for the four test velocities, which meant that the cooling rate of high jet velocities (7.8 m/s, 12.0 m/s) was faster than the low jet velocities (3.5 m/s, 4.8 m/s). Therefore, the DNB temperature was not identified. For lower jet velocities, DNB temperatures were in the range of 500 °C to 640 °C. It is obvious that the lower the velocity, the earlier DNB temperature was identified along the distance from shooting point.

At shooting position, there was only nucleate boiling and convection during the whole experiments. As shown in Fig. 7(a), the four cases followed the same trend, which indicated that the effect of jet velocity on shooting point (x=0 mm) was not significant. The higher the jet velocity, the greater the heat flux. For x=40 mm, as is shown in Fig. 7(b), transition boiling occured only in the lower jet velocities (3.5 m/s and 4.8 m/s). In addition, the temperature region of nucleate boiling for lower jet
velocity was wider than the higher jet velocity. All the above experimental results showed that for jet cooling, the cooling effect was very strong, so the effect of jet velocity was not obvious. The complete boiling curve was only seen at the lower jet velocity, while for the higher jet velocity experiments, only a part of the boiling curve was seen.

![Figure 7. Boiling curves at x=0 mm and x=40 mm for different jet velocities.](image)

5. Conclusion
An experimental work was conducted to explore the effect of jet angle and jet velocity on cooling process. After examining the results, the following conclusions were drawn.

1. The Leidenfrost point was not captured due to the strong cooling effect of jet impingement.
2. Jet angle played a vital role in promoting cooling process, especially for Nicrofer. The smaller the jet angle, the faster the quenching rate. The angle of 25° presented the most optimum cooling effect.
3. Jet velocity had a great influence on quenching. The faster the jet velocity, the shorter the cooling time. For the maximum jet velocity in this experiment \( v = 12.0 \text{m/s} \), DNB temperature even was not identified. While for the rest velocities, the influence on DNB was not great, from 450 °C to 550 °C.

This research is of great significance to help understand the jet quenching process and optimize the cooling rate of materials. Further study will be performed on the jet cooling in terms of changing the type of coolant and the effect of coolant temperature on the cooling rate.

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