Applied Thermal Engineering 100 (2016) 902–910

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Heat transfer characteristics during jet impingement on a high-temperature plate surface

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HIGHLIGHTS

- The influenced parameters of the impinging jet were systematically studied.
- The wetting characteristic along the radial direction was investigated.
- The rewetting temperature highly depended on the initial plate temperature.
- A regression equation was established to predict the maximum heat flux.

ARTICLE INFO

Article history:
Received 8 October 2015
Accepted 20 February 2016
Available online 4 March 2016

Keywords:
Ultra-fast cooling
Heat transfer
Jet impingement
Rewetting phenomenon

ABSTRACT

The heat transfer ability and cooling uniformity in ultra-fast cooling technology played a critical role in improving the microstructure and mechanical properties of hot rolling steel. However, the heat transfer characteristics and boiling phenomena during the cooling process of a water jet impinging on a hot plate surface approximate to the industrial conditions were rarely reported. Herein, we investigated the effect of the initial surface temperature, water temperature, and jet velocity on the heat transfer characteristics for the industrial applications. The results revealed that the rewetting front propagation was considerably affected by the growth and detachment of the bubbles in the rewetting front region. The wetting delay time was extended by the superheat increase, and the sub-cooling and jet velocity decrease, because the ability to condense the bubbles was weakened in the front rewetting region. Meanwhile, the wetting velocity varied with the distance from the stagnant point. Moreover, the maximum heat flux, q_{max}, was influenced by the initial surface temperature, water temperature, and jet velocity; finally, a regression equation was established to predict the q_{max} value. The information provided in this work would be beneficial for predicting and optimizing the industrial applications of ultra-fast cooling technology.

1. Introduction

Thermo-mechanical control process (TMCP) technology has been used extensively for steel production because of its significance in improving the microstructure and mechanical properties of hot rolling steel. Laminar cooling has been considered as the dominant cooling form in the controlled cooling process in the steel industry. However, its cooling ability and uniformity are largely constrained by the residual cooling water on the plate surface. Recently, ultra-fast cooling (UFC) [1–3] was developed using water jet impingement technology with a heat flux greater than 10 MW/m^2 [4], which played a significant role in industrial applications in metal processing.

Over the past few decades, numerous efforts were devoted to investigating the factors that influenced the heat transfer of jet impingement. Liu et al. [5] investigated the drawing quality of specially killed steel and stainless steel plates cooled by the impinging jet with water temperatures of 13 °C and 30 °C and a constant flow rate of 60 L/min. However, when the jet velocity ranged from 5.6 to 6.5 m/s, the boiling curves displayed the existence of transition and nucleate boiling during the cooling process. It is concluded that the cooling rate was significantly influenced by the water temperature, by which the cooling intensity increased with a decrease in the water temperature. Meanwhile, higher sub-cooling also led to a larger initial impingement area. In addition, much attention was paid by Aamir et al. [6] on the cooling performance of plates with different initial plate temperatures. They found that the boiling curves were severely influenced when the initial plate temperature increased from 600 to 900 °C. What's more, the transient heat transfer using a circular water jet impingement was experimentally investigated by Ochi et al. [7]. The higher heat flux at the stagnation point (in the central region), when compared with its peripheral area in the radial direction, was observed on a flat plate. In the stagnation region, the heat flux increased with the water sub-cooling and jet velocity. Their observation also revealed that the rewetting velocity increased with

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http://dx.doi.org/10.1016/j.applthermaleng.2016.02.054
1359-4311/

the enhancement of nozzle diameter, jet velocity, and water sub-cooling. Meanwhile, other researchers [8–11] focused on the rewetting phenomenon during the water jet impingement process and concluded that rewetting during transient cooling can be regulated by influence parameters, such as the rewetting temperature and the rewetting delay time. Also, the rewetting has been severely influenced by the liquid sub-cooling and flow rate.

The information from the previous literature had provided a profound insight into the impingement jet. However, most of the conclusions in these works were isolated from the practical cooling conditions in the industries. In addition, the obvious discrepancy in conclusions from similar studies conducted under different experimental conditions was observed. For example, similar experiments were carried out by Mozumder et al. [12] and Kumagai et al. [13], respectively; however, the resulted maximum heat flux (MHF) varied from 4 and 6.5 Mw/m^2. In order to reduce the deviation of experimental data and facilitate the contrast between experiments, it is necessary to investigate the influencing parameter with similar measurement and calculation accuracy. Therefore, in this work, the experiments were carried out on the same equipment for the consistent error. The effect of individual parameters such as the water jet temperature, surface temperature, and jet velocity on the practical industrial applications was investigated systematically. Meanwhile, the equations of the maximum heat flux were regressed. What is more, the results herein can be used to predict and optimize the cooling ability and uniformity of a cooling device.

2. Experiment setup and produce

Fig. 1 illustrates the experimental system, which consisted of a water tank, a water supply pump, a thermometer (used to measure the water temperature), thermocouples, a data acquisition system, a test chamber, and a test plate. The velocity of cooling water was pumped in the range of 1.5–30 L/min, which is measured by a flow meter. The vertical distance between the nozzle exit and test plate surface can be adjusted for the maximum height of 400 mm to the minimum height of –400 mm. The nozzle head is compatible with those employed in the steel industry.

An AISI 304L steel plate with dimensions of 20 mm × 80 mm × 150 mm was used owing to its stable properties [14]. The physical parameters of stainless steel, such as the diffusivity, conductivity, and specific heat, were shown in the reference [15]. Also, 3-mm Type K Chromel–alumel thermocouples were used to measure the temperature at a position –2.5 mm below the plate surface. A data acquisition system with ten channels was used to collect the data from the thermocouples at an acquisition rate of 10 points per second. As shown in Fig. 2, along the longitudinal

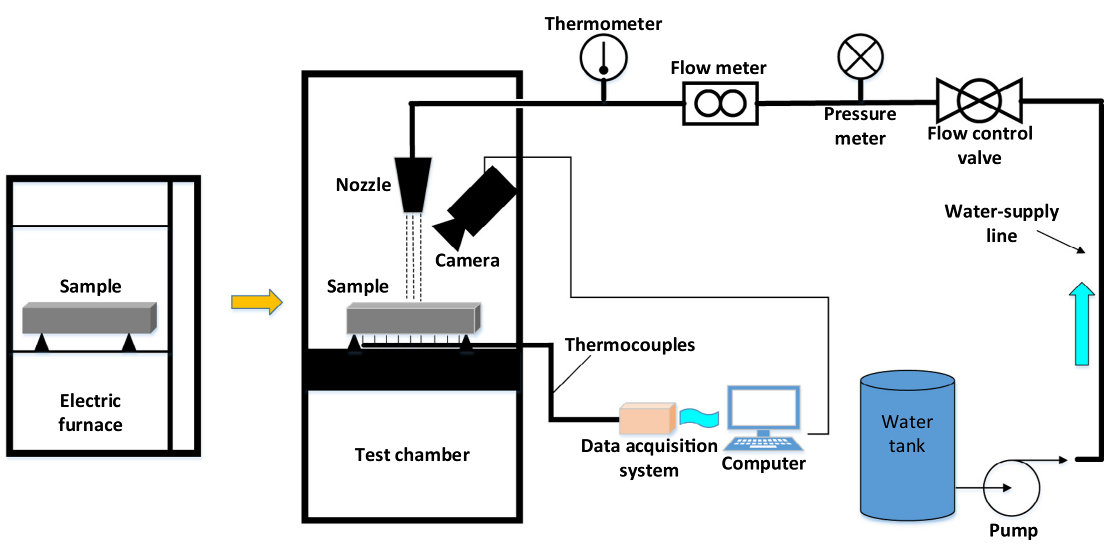

Fig. 1. Schematic of the experiment facility.

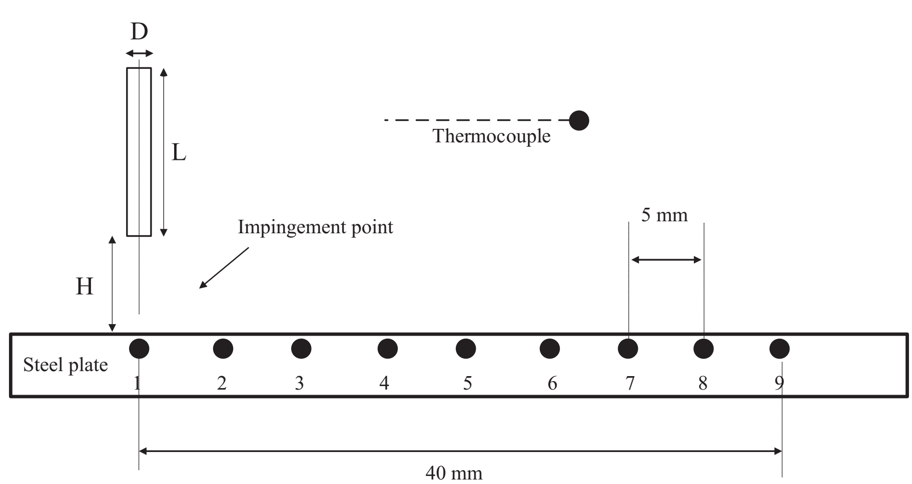

Fig. 2. Jet impingement prototype and arrangement of thermocouples.