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Heat transfer characteristics of water spray impinging on high temperature stainless steel plate with finite thickness

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A R T I C L E I N F O

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Experiments for full cone water spray cooling of high temperature metal plate are carried out at different water pressure levels. The heat flux is obtained by solving a 1D inverse heat conduction problem, and the accuracy of the heat flux is verified by 3D heat conduction analysis. Water flux significantly influences transition boiling, critical heat flux, and Leidenfrost point, with the increase in water pressure driving critical heat flux and Leidenfrost point to a higher surface temperature region. By contrast, water flux has very limited effect on nucleate boiling regime, and all the heat flux curves merge into a narrow band. The heat flux in the nucleate boiling regime is mainly depends on surface temperature. The empirical correlations for critical heat flux and transition boiling regime are obtained as function of Sauter mean diameter, local water flux, surface temperature, and physical properties of water and vapor. The local water flux is suitable for obtaining the local heat transfer characteristics of spray cooling, given that the spatial distribution of spray flux is non-uniform.

1. Introduction

The spray cooling technology has drawn increasing concern for electronics cooling, steel strip/plate cooling, casting, and other high heat flux applications. Spray cooling exhibits the characteristics of high heat transfer, uniform heat removal, small fluid inventory, low droplet impact velocity, and absence of temperature overshoot. The results obtained by Labergue et al. [1] under the same water flux and surface temperature range indicate that: (1) the space-averaged cooling efficiency of liquid jet is lower than spray; (2) the coolant fluid consumption of spray is only 51% of liquid jet; (3) the liquid jet exhibits higher heterogeneity of the cooling rate at the surface. Bostanci et al. [2] experimentally studied the effect of enhanced surfaces on CHF using a vapor atomized spray nozzle and ammonia as working fluid. The enhanced surfaces can achieve CHF values of approximately 11.0 MW/m^2 with 67% spray cooling efficiency based on liquid usage. The ultra-high heat flux removed by spray cooling in the experiments can reach up to 12 MW/m^2 using water as a coolant with a relatively small fluid inventory [3]. However, the heat transfer mechanisms of spray cooling are not totally understood. Given its dependence on many parameters that are not easily varied independently, the predictive capabilities of spray heat transfer mechanisms are limited [4].

The characteristics of spray cooling are affected by fluid pressure, mean velocity of the sprayed fluid, droplet size (such as Sauter mean diameter d_{32} and mean volume diameter d_{30}), fluid flux density, nozzle to surface height, nozzle type, angle of spray, subcooling of fluid, and so on [5,6]. The complex nature of the interaction of liquid and vapor phase, droplet impact, and phase change makes it difficult to understand the heat transfer phenomena [5,6]. Thus, the experiment is an important method used to obtain the characteristics of spray cooling under various working conditions.

Monde et al. [7] argued that critical heat flux (CHF) should scale according to the Weber number, density ratio, and the Jakob number. Note that the characteristic size is based on the diameter of heated surface in their study. The experimental results obtained by Chen et al. [8,9] indicate that droplet velocity has the largest influence on CHF, followed by droplet flux, while droplet diameter has negligible effect.

Estes and Mudawar [10] systemically studied the Sauter mean diameter and critical heat flux for full cone spray cooling of small surfaces. A correlation for Sauter mean diameter was successfully obtained for fluid, such as FC-72, FC-87 and water, which have vastly different values of surface tension. Heat transfer experimental results reveal that (1) increasing water flux density or decreasing d_{32} and subcooling results in both the single-phase heat transfer coefficient and the critical heat flux q_{CHF} increasing; (2) the nucleate boiling data convergence onto a single line, which

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depicts that the water flux density and droplet diameter (d_{32}) have very limited effect on the nucleate boiling regime; and (3) by combining the correlations for critical heat flux and Sauter mean diameter, it is possible to predict accurately CHF for full cone sprays without having to conduct expensive and laborious drop sizing measurements for each individual nozzle.

Liu, Morsi, and Clayton [11] carried out a systematic experimental study on heat transfer characteristics from the hot die surface to the water spray. They obtained a new empirical correlation that relates spray cooling heat flux in nucleate boiling, critical heat flux, and transition boiling regimes to spray hydrodynamic parameters such as liquid volumetric flux, droplet size, and droplet velocity. The authors stated that the correlation is only suitable for predicting the spray cooling heat flux involved in a high pressure die casting process with water as coolant.

Ruiz [12] carried out an experimental study of water spray cooling using mono-dispersed droplet sprays impinging on a flat and heated surface. An empirical model for the nucleate boiling regime and critical heat flux was obtained. The parameters in this empirical model include diameter and velocity of the droplet, mass flow rate, ambient pressure, sub-cooling degree, and surface roughness.

Jia and Qiu [13] conducted an experimental investigation on droplet dynamics and heat transfer in spray cooling. They concluded that the expulsion rate, which is the ratio of outgoing to incoming mass fluxes, can be used to explore the mechanism of spray cooling heat transfer. They found that using a surfactant leads to a relatively low superheat cooling condition under high heat flux cooling requirements; the addition of a surfactant to a working fluid (water) broadens the CHF temperature range. For spray cooling using pure water, the critical heat flux increases parabolically with the mass flux of water, and the critical temperature corresponding to CHF increases linearly with mass flux. Dissolving the surfactant has little influence on the value of CHF, and a linear relation was found between water mass flux and CHF upon adding a surfactant.

Wendelstorf et al. [14] experimentally studied the heat transfer characteristics of full cone nozzles with water as coolant. The experimental conditions include surface temperature between 200 and 1100 °C, spray water temperature around 18 °C, and water spray density between 3 and 30 kg m^{-2} s^{-1}. The obtained an analytic correlation for heat transfer coefficient as a function of water spray density and temperature difference between surface and water based on the experimental data.

Spray angle and pressure can greatly affect the performance of spray cooling. Ravikumar et al. [15] studied the effect of spray inclination on the cooling of hot steel plate. Their results indicate that the cooling rate and critical heat flux of pure water spray increase with an increase in spray inclination up to an optimum angle of 30°. Yan et al. [16] used R134a as working fluid in multiple inclined and normal spray cooling experiments. They observed that increasing the mass flow rate and pressure drop across the nozzles improved the heat transfer coefficient, with a maximum enhancement of 117% and 215% in inclined and normal sprays, respectively. Horacek, Kiger, and Kim [17] investigated single nozzle full cone spray cooling heat transfer mechanisms using varying amounts of dissolved gas. They stated that the uncertainty regarding spray cooling heat transfer mechanisms is primarily attributed to difficulties in obtaining local measurements of heat transfer and observing the state of the liquid on the surface. They concluded that the presence of dissolved gas increased the effective subcooling of the liquid, shifted the spray cooling curves to higher wall temperatures, and increased the critical heat flux.

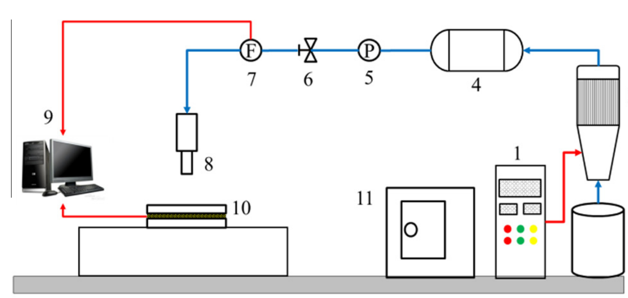
This current study focuses on water spray cooling in stainless steel strip/plate heat treatment processes. In continuous heat treatment line, the stainless steel is heated up to 800–1100 °C for several minutes, and then cooled to 400 °C in a very short period (usually less than 1 min) according to heat treatment cycle. In the cooling section of the heat treatment line, water spray cooling is employed because it removes heat more efficiently than air jet impinging. Additionally, there is absence of temperature overshoot. And this technology produces a very uniform temperature distribution. The uniformity of temperature distribution is critical for steel strip buckling [18] and warpage [19]. A full cone spray nozzle was used in all the experiments. The heat flux at different water pressure levels were obtained by inverse heat conduction analysis. Finally, the empirical correlations for the transition boiling regime, the nucleate boiling regime, and CHF were obtained.

2. Experimental facilities

The experimental setup is schematically shown in Fig. 1. The setup includes a heating furnace, a water pressure controlling unit, a water tank, a water pump, a pressure vessel, a pressure gauge valve, a volume flow meter, a spray nozzle, and a data acquisition computer. The electric heating furnace can heat the test plate up to 1000 °C. The water supply system, which includes water pressure controlling unit, water pump, water tank, and pressure vessel, can continuously and steadily supply high-pressure water in the region of 0.2–2 MPa, within an error range of ±0.005 MPa. A full cone spray nozzle 3/4F-JJXP-30 made by H.IKEUCHI & CO., Ltd. was used in this research, the nozzle diameter is 5.0 mm, spray angle is 85°, and the water spray capacity is 30, 35.4, 43.6 and 50 l·min^{-1} at pressure 0.2, 0.3, 0.5 and 0.7 MPa respectively; the distance from the nozzle to the top surface of the target plate is H_n = 250 mm as shown in Fig. 2.

K-type thermocouples were used to detect the temperature of the target plate. A data acquisition computer (NI PXIe-1078 with NI TB-4353 card) recorded the target plate temperature at a maximum recording frequency of 80 Hz for each thermocouple. The water temperature was detected using a mercurial thermometer which is not shown in Fig. 1. The water temperature was maintained in the range of 15 ± 1 °C in all the experiments.

As shown in Fig. 3, the test plate used in this research has a square shape and consists of three layers: a target plate (as shown in Fig. 2) layer on top, a thermal insulating material layer in the middle, and a bottom cover layer at the bottom. The test plate was fixed on an experimental platform during the experiments. The insulating material can maintain an insulated boundary on the bottom side of the stainless steel target plate, which simplifies the solution of inverse heat-conduction problem. The thermal properties of the insulating material are listed in Table 1. The grade of the stainless steel target plate is SUS 304; its chemical composition is provided in Table 2 [Taiyuan Iron & Steel (Group) Company Ltd.]. The stainless steel plate has a density of 7920 kg m^{-3}. The temperature dependent conductivity and specific heat of the target



1 Water pressure controlling unit; 2 Water tank; 3 Water pump; 4 Pressure vessel; 5 Pressure gauge; 6 Valve; 7 Volume flow meter; 8 Spray nozzle; 9 Data acquisition computer; 10 Stainless steel target plate; 11 Heating furnace

Fig. 1. Experimental setup of the water spray system.