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Subcooled water jet quenching phenomena for a high temperature rotating cylinder

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ABSTRACT

Quenching characteristics of a rotating hollow steel cylinder with 15 mm water jet having flow rate of 6–10 L/min has been experimentally investigated. The jet with 60–80 K subcooling was impinged on the horizontally rotating (0, 15, 30 and 60 rpm) 460–560 °C hot cylinder. A developed inverse solution estimated surface temperature and heat flux from measured temperatures during quenching. Surface rotation created a non-uniform cooling which resulted in a non-uniform distribution of wetting front (leading edge of visible vigorous boiling region). Surface velocity (rotation) strongly influenced relative velocity between solid and liquid which affected the surface heat transfer during cooling. As the cylinder rotated and the jet was fixed, the surface heat flux fluctuated which was followed by the surface temperature. Heat transfer from a relatively faster moving surface was smaller but due to periodic cooling, bulk temperature reduced more. The estimated heat flux agreed reasonable with static surface critical heat flux in literature especially for the trend with radial position. The produced boiling curves were well compatible with some of the compared correlations in nucleate boiling region.

1. Introduction

For optimizing mechanical properties of materials, cooling rate is important in manufacturing industries. Among various cooling process, jet impingement cooling is the most effective one. Faster cooling is designated as quenching in heat transfer science. Quenching knowledge is also applied in fire fighting, electronic cooling, emergency cooling during LOCA (Loss of Coolant Accident) in nuclear reactor. Quenching involves nucleate boiling, film/partial film boiling, single phase convection, forced convection, homogeneous/heterogeneous nucleation (which changes flow pattern and heat transfer characteristics), solid–liquid interaction and many other combined modes of heat transfer. Many of these dominating parameters make the quenching an intricate heat transfer process.

A number of quenching studies have been initiated from a few decades before. Investigation in experimental/numerical way with different dominating parameters of jet impingement/spray quenching on both static surface by Marie et al. [1], Monde et al. [2], Chen [3], Xu and Gadala [4], Mozumder et al. [5], Omar et al. [6] and dynamic surface by Chattopadhyay et al. [7], Volle et al. [8], Cho et al. [9], Nasr et al. [10] have been performed to grasp the inherent characteristics of quenching mechanism. Jet quenching on moving surface is very much resembles with Run out Table (ROT) in steel manufacturing industry. Fundamental modes of heat transfer and some basic mechanisms remain same for both static and moving surfaces. Due to the involvement of surface velocity, quenching with moving surface becomes more complicated to analysis.

Karwa et al. [11] experimentally studied hydrodynamics of jet impingement quenching of a stainless steel cylindrical specimen. They found that water film outside the wetted region was deflected away from the surface and then broke into droplets due to surface tension and shear forces. They also observed that although the wetted region may appear devoid of any bubbles, strong two-phase flow occurred within this region. Experimental and numerical investigations were carried out by Gradeck et al. [12] with impinging jet on a moving plate for various jet and plate velocities as well as for various nozzle diameters and heights. The position of hydraulic jump was measured by visualizations. A power relation was derived for calculating the radius of the jump in which the Reynolds and Weber numbers took place even if it appeared that the main parameters were the dimensionless velocity and the dimensionless height. Their turbulence modeling based on a k–e model and near-wall treatment showed that quantitative results were quite good compared to the experimental one. Karwa et al. [13] again performed an experimental study of heat transfer during quenching of a cylindrical stainless steel test specimen of

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Nomenclature

CHF	critical heat flux (M W/m^2)
D_o	outer diameter (mm)
D_i	inner diameter (mm)
d_j	jet diameter (mm)
h_{dry}	heat transfer coefficient of dry region (M W/m^2 K)
h_{wet}	heat transfer coefficient of wet region (M W/m^2 K)
L	length (mm)
N	rotational speed of cylinder (rpm)
Pr	pressure (Bar)
Q	liquid flow rate (L/min)
q_{ws}	surface heat flux (M W/m^2)
$q_{ws(max)}$	surface maximum heat flux in a cycle (M W/m^2)
r_{wf}	wetting front position (mm)
t	time counted from first impingement of jet (s)
t^*	resident time (s)
T_{bo}	solid initial temperature (°C)
T_{liq}	liquid temperature (°C)
T_{sat}	saturated temperature of liquid (°C)
T_{ws}	surface temperature (°C)
V_j	jet velocity (m/s)
V_{rev}	relative velocity between solid and liquid (m/s)
V_{surf}	solid surface linear velocity (m/s)
WF	wetting front
Greek symbol	
θ	angular position on solid surface around the impinged centre (°)
ΔT_{sat}	wall superheat (K)
ΔT_{sub}	liquid subcooling (K)

about 900 °C. Subcooled water jet was directed onto the upward facing flat face of the cylinder. They found three distinguished regions (wetted region, transition region and un-wetted region) which are also observed in the present study.

Robidou et al. [14] performed experiments under steady-state conditions to study boiling heat transfer from a hot plate with a planar jet of water. For their case, a temperature control of the heating surface enabled the determination of entire boiling curves and the identification of each boiling regime from forced convection to film boiling. They found in the forced convection regime, the heat flux increased with an increase of subcooling, jet velocity and decreased of the distance from the stagnation line. Boiling first started in the parallel flow region and propagated in the direction of the jet. A hybrid scheme combining experimental and numerical methods has been developed by Chen et al. [15] to study heat transfer in the case of a circular jet impinging on a moving metal plate. They found that the overall cooling efficiency was better for the moving case than for the stationary. An analytical study of heat transfer by jet impingement was conducted by Timm et al. [16] for high heat flux (larger than 10 MW/m^2) on red hot static steel plate. They interestingly found that sufficient high degree of subcooling and jet velocity prevented the formation of a vapor film, even if the wall super heat is larger. Karwa et al. [17] further developed a simplified two-phase analytical model for predicting the Leidenfrost point of a planner and circular liquid jet impinging on a flat hot static wall. Their model predicted that the Leidenfrost temperature was independent of jet velocity at a fixed subcooling. The model for planar jet underpredicted wall heat flux in the range of 5–47% and wall superheat in the range of 40–70%.

Gradeck et al. [18] again performed an experimental investigation for quenching of a hot static and rotating cylinder with initial temperature of about 500–600 °C by a subcooled planar water jet. In the case of static surface, the measurements confirmed the existence of a "shoulder of flux" in the stagnation zone of the jet. In the case of a moving surface, the maximum of heat transfer (for a given regime) is moving during the cooling time from downstream (film boiling regime) to upstream (forced convection). An innovative experimental quenching device was investigated by Devynck et al. [19] for analyzing the effect of the wall velocity of the surface to be cooled on the boiling curves and they observed that the shoulder of heat flux was strongly dependent on the surface to jet velocity ratio. They also found that a very small increase of the wall velocity had a high influence on shoulder of flux collapse.

Heat transfer characteristics associated with water spray and jet cooling used in rolling process were studied by Chen and Tseng [20]. The effect of important convective heat transfer parameters on cooling performance for both stationary and moving surfaces were examined by them. They found that the surface motion increased the cooling efficiency of roll and strip cooling. They also concluded that the surface motion substantially influenced the local heat transfer behavior. A simplified model was adopted by Liu and Wang [21] for predicting heat transfer characteristics of film boiling of water jet impinging on flat plate at stagnation zone. Experiments were also conducted by them for comparison of their predicted values. Water subcooling provided strong effect on heat transfer characteristics. Transition boiling occurred for highly subcooled water jet impinging. Film boiling occurred for only subcooled water jet impinging. Wall heat flux increased with square root of the subcooling. Recently, Mozumder et al. [22] performed an experimental investigation on subcooled water jet impinging quenching for a rotating cylinder. They found that the heat transfer characteristics were greatly influenced by surface velocity.

Wang et al. [23] performed experiment under transient conditions to investigate heat transfer phenomena of stationary hot steel plate under multiple top circular jets on run-out table. Based on inverse heat conduction model, a two-dimensional finite difference program had been developed to calculate local surface convective heat transfer coefficients and corresponding temperatures. They observed that cooling flow rate had no effect on heat transfer coefficient and surface temperature at stagnation point. The surface temperature had a significant effect on heat transfer coefficient during cooling. With decreasing surface temperature, the heat transfer coefficient gradually increased at above 300 °C. Below this surface temperature, the heat transfer coefficient increased drastically faster at stagnation line. Volle et al. [24] conducted an analytical study to verify the feasibility for the estimation of heat fluxes during cooling of a rotating cylinder by an impinging jet. A semi-analytical method had been developed for their two-dimensional inverse heat conduction problem (IHCP) using Laplace and Fourier transforms technique. The simulations of inversion for two representative test cases showed that the estimated surface heat flux is not biased and they concluded that it can therefore be reconstructed. An analytical solution to inverse heat conduction problems with a far-field boundary condition was derived by Woodfield et al. [25] for one and two-dimensional problems using a Laplace transform technique. Accuracy of the predictions was improved by superposition of successive corrections to the function used to approximate the measured data. Long-term history of high frequency modes in both time and space is neglected noting that these components do not penetrate deeply into the solid. Their