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Quasi-steady front in quench subcooled-jet impingement boiling: Experiment and analysis

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ABSTRACT

Boiling heat transfer of subcooled water jet impingement on highly superheated plate is investigated with heat transfer analysis and high-definition flow visualization. The stainless steel plate initially heated up to 900 °C by an induction heating is quenched with the water temperature of 15 °C. The surface temperature and heat flux are estimated by solving 2-D inverse heat conduction problem. The temporal visualization during quench subcooled-jet impingement boiling is synchronized with the heat transfer measurement in the corresponding surface temperature and heat flux. Spread of the subcooled jet over the horizontal plate shows a quasi-steady regime where the wetting front spreads linearly with time. The time for onset of the quasi-steady regime can be explained by a quasi-steady time. The front separates the single-phase/collapsed-bubble region from the outside region which is dry if not for the impinging droplets ejected from the front. As the front expands, the surface experiences a sequence of single-phase, collapsed-bubble, wetting front evaporation and ejected-droplet evaporation cooling. The fraction of water ejected from the front increases linearly with time (reaches over 10%) and is also predicted.

1. Introduction

In material processing, the quenching processes strongly control the phase transformation, grain size distribution and thermal stresses of metallic work pieces. Water jet impingement has been widely used for its rapid and intensive cooling capacity [1–5]. The surface morphology, structure and composition of the quenched steel are also characterized by the initial heating and then the cooling rate during quenching process. However the fundamental studies of this cooling process are rather sparse due to complexity of its transient, heterogeneous boiling modes, in particular for subcooled jets. The boiling heat transfer is also affected by the dimensions and thermal properties of the quenched material (metallic). So, a thorough understanding of boiling heat transfer, including the hydrodynamic of the jet impingement, is required for predicting the characteristics and the qualitative improvement in material. Here we aim at providing further insights into the jet quench boiling and Fig. 1 gives a schematic of the subcooled circular free-surface jet flowing over a highly superheated surface, showing three different regions, namely the wet, wetting front, and dry region. Furthermore, at the stagnation point shortly after cooling commences, and under high local heat flux (cooling rate), evaporation is suppressed, and single-phase convection cooling continues there. At larger radial locations, the surface temperature is in high and due to the subcooled jet, the region of collapsed-bubble boiling prevails. Further outward, the dry region is reached with an active droplet spouting evaporation front. The otherwise dry region is not cooled by landing of these droplets which evaporate with intensity depending on the local landing site surface superheat.

A review of prior experimental investigations into the characteristics of jet impingement quenching is given by Wolf et al. [6], covering the hydrodynamics of the jet flow, various boiling regimes, and key jet-surface parameters. But, few experiments regarding rapid cooling on a high-temperature surface over 500 °C were investigated due to complicated coupled boiling heat transfer in highly unsteady cooling. The visual observation reveals formation of “dark zone” (contrast by glowing high superheat region) beneath the jet (Karwa et al. [7]) with the surface temperature there under 500 °C with the peripheral boundary of this zone called the wetting front. The liquid deflection was observed outside of wetting front due to surface tension and shear forces. These splashed droplet velocity is governed by jet velocity. Hall et al. [8] and Ishigai et al. [9] reported that film boiling was not observed in the stagnation region with highly subcooled jet, even though an

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Nomenclature

A	area, m^2
D_n	diameter of circular nozzle, m
L_n	height position of nozzle, m
q	heat flux, W/m^2
r	radial distance from stagnation point, m
R_{do}	wetting front radius, m
Re_D	nozzle Reynolds number
Σ	sum of squared function
T	temperature, °C
u	velocity, m/s

Greek letters

α	thermal diffusivity, m^2/s
β	fraction of liquid undergoing phase change
μ	viscosity, Pa s
ρ	density, kg m^{-3}
τ_{qs}	quasi-steady time, s

Subscripts and superscripts

n	nozzle
ini	initial
qs	quasi-steady
sat	saturation
sc	subcooling
sur	surface
sh	superheat

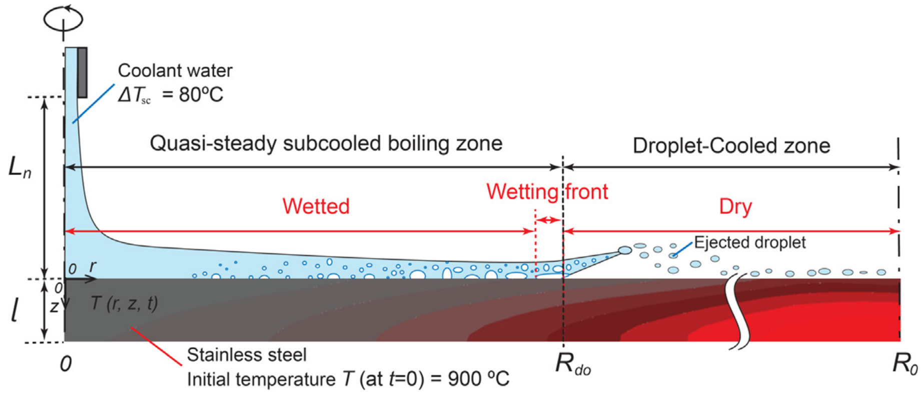

Fig. 1. Axisymmetric schematic of spreading of subcooled water circular jet over a superheated horizontal plate, showing the geometric parameters, flow regimes, and plate transient conduction.

initial temperature reaches about 1000 °C. They concluded that a direct contact between the coolant and surface in the stagnation region occurred without any noticeable period of film boiling. At the stagnation point, minimum heat flux of film boiling decreased with increasing nozzle diameter and increased with jet velocity and subcooling. Monde and his co-workers [10–14] have studied a jet impingement boiling heat transfer on different metal surfaces like as copper, brass and carbon steel with relatively low initial temperature (under 500 °C). Woodfield et al. [10] investigated the flow behavior and quenching sound with a high-speed video camera and microphone. They suggested that flow phenomenon can be changed depending on the initial temperature, and the changed flow pattern was accompanied by different boiling sound. Hasan et al. [14] developed a mechanistic model to describe the homogeneous nucleate boiling of jet impingement by applying the concept of 1-D semi-infinite heat conduction. Toghraie et al. [15,16] performed numerical analysis about the subcooled jet boiling on hot surface with 800 °C. Volume of fluid method was adopted to track the evolving free-surface between two or more fluids. They numerically confirmed that the increase of jet velocity and subcooled temperature caused an improving in cooling rate and high rewetting temperature. Existence of maximum heat flux ($q_{\max}$) in quench boiling is experimentally by Mozumder et al. [17] and Hammad et al. [18] and they found that $q_{\max}$ occurs in the nucleate boiling region or boundary between the nucleate boiling and transition boiling region. They also reported that the boundary is in the fully-wetted region and its location varies with the surface wetting conditions. However, boiling heat transfer characteristics with very high superheat and larger plate surface area are clearly investigated by their theoretical analysis.

The object of this study is to investigate using high-resolution imaging and analyse the hydrodynamics of round, subcooled (80 °C subcooling) water jet (jet Reynolds number of 15,000) quench boiling of large stainless-steel plate area under very high initial temperature (900 °C). We use the axisymmetric inverse heat conduction problem (IHCP) to determine the transient plate temperature distribution, and predict the transient surface heat flux distribution. We explain the various boiling regions (spatial) and regimes (temporal), including the presence of a quasi-steady cooling behavior.

2. Experiment and methods

2.1. Experiment

The experimental setup is schematically shown in Fig. 2, and the components are heat flux gauge, flow loop and data acquisition system (DAQ). The flow loop consists of water reservoir, pump, electromagnetic flowmeter, water chamber and the jet nozzle. The water coolant temperature is maintained with 20 °C (±0.5 °C) with a constant-temperature reservoir composed of insulated stainless-steel tank of 700 liter, electric heater of 10 kW, and chiller for water temperature control. The coolant of water can be deliv-