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Water jet impingement boiling from structured-porous surfaces

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ABSTRACT

Structured-porous surfaces were created by diffusion bonding a single layer or multiple layers of highly conductive copper wire mesh screen onto plain heat transfer base surfaces. Flow boiling heat transfer experiments were then conducted with a liquid water jet impinging onto those porous copper surfaces under atmospheric pressure. For comparison, experiments of jet impinging on a plain copper surface were also conducted. The effect of jet Reynolds number, jet inlet subcooling, and porous layer thickness on boiling heat transfer were explored. Surface ageing and data repeatability were also discussed. The results show that a base surface heat flux of 674 W/cm^2 was reached at a superheat of 5 K and a jet Reynolds number of 10,000 with a four-layer 200-mesh test surface. Compared to jet impinging on a plain copper surface under identical working conditions, a fourfold performance enhancement was obtained in increasing heat transfer from the base surface.

1. Introduction

Demands for efficient cooling technologies have never become more evident and urgent than today, when considering the powerful computing devices such as data centers, smart-phones and tablets now in use. The small footprints and concentrated power loading in those systems call for development of innovative heat transfer technologies that can efficiently cool hot spots and create uniform temperature distribution.

Liquid jet impingement heat transfer is a potential candidate due to its proven ability to achieve high heat fluxes at relatively low superheats (or high heat transfer coefficients) with plain or enhanced surfaces [1–3]. This is particularly true for jet impingement boiling. Generally, the superior heat transfer performance of liquid jet impingement is attributed to the fact that the impinging jet decreases the thickness of the liquid film on the heater surface, and thus reduces the thermal resistance between the heater surface and impinging flow. In addition, intensive flow mixing also plays a role.

Understandably, liquid jet impingement heat transfer is most efficient at the impinging region and becomes less so with increasing distance from the stagnation zone. For a single impinging jet, this can lead to non-uniformities in temperature distribution in the target plane. On the other hand, due to design constrains, such as impacting stress, pumping power, and reliability, impinging regions are generally small. In other words, the high heat transfer coefficient is only prevalent in a small area, which is less desirable in some applications.

To improve temperature uniformity and to achieve higher heat transfer performance, various concepts of combining jet impingement cooling with other heat transfer technologies have been proposed. A hybrid of jet impinging and microchannel cooling has been studied in [4–7]. Specifically, in [4], Jang et al. experimentally investigated a microchannel heat sink subjected to an air impinging jet. They demonstrated that, under certain conditions, up to 48.5% cooling efficiency improvement was achieved compared with that achieved with classical microchannel design, with pressure losses reduced by 90.5%.

Hybrid cooling scheme of jet impinging onto finned surfaces has also been investigated. Li et al. [8] studied both experimentally and numerically the thermal-fluid characteristics of plate-fin heat sinks cooled by impinging jet by varying parameters as the impinging Reynolds number, the impingement distance, the fin width, and the fin height. Guo et al. [9] fabricated four different types of pin fins on surfaces of silicon chips using dry etching technology. They experimentally studied the heat transfer performance using FC-72 jet impinging on those finned surfaces and concluded that, for a fixed condition, all micro-pin–finned surfaces undergo a considerable heat transfer enhancement compared to a smooth surface.

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Nomenclature

C	mesh screen constant (–)
cf	compactness factor (–)
d	wire diameter (mm)
d_h	pore hydraulic diameter (mm)
d_{jet}	jet diameter (mm)
h	averaged heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	distance from the center of the type-T thermocouple to the top surface of the heat flux gauge (mm)
$\dot{m}$	mass flow rate (kg/s)
M	mesh number, defined as wires per linear inch (in.)
K_{AR}	area ratio, $K_{AR} = 9$ (–)
K_{LLS}	coefficient of the least linear square fitting (K/mm)
P	pressure (kPa)
q''	heat flux (W/cm^2)
Re_{jet}	jet Reynolds number
T	temperature (K)
T_i ($i = 1,\ldots,5$)	temperature readings of five thermocouples installed in the heat flux gauge (K)
x	coordinate system

Greek symbols

β	specific surface area, (1/m)
ϵ	porosity (–)
Δ	difference
μ	dynamic viscosity (Pa s)

Subscripts

b	base heat transfer surface
cu	copper
sat	saturated state
sub	subcooled state

Part of the performance enhancement is attributed to the increased total surface area. They also argued that the micro-convection in the fin gaps helps improve the critical heat flux.

Metallic porous media are known for possessing a large number of interconnected or discrete pores and a high surface area to volume ratio (specific surface area). If attached to a boiling surface with properties tuned appropriately, the formed porous surface can serve as an effective boiling promoter. The boiling enhancement mechanism of such surfaces was summarized by Thiagarajan et al. [10], as a combination of the following factors: an increase in the effective surface area, an increase in the nucleation sites density, the presence of capillary forces that facilitate liquid flow, and the dependence of the vapor escape path on the pore distribution in the layer adjacent to the liquid.

Jet impingement onto and through porous structures has also gained interests from a few researchers, though majority of those works are numerical based, and are only concerned with the single-phase mixed convection in the porous layer. A recent numerical study by Lemos and his co-workers [11,12] considered a jet impingement cooling on a heated plate covered with and without a porous layer. They investigated the effects of porosity and thickness of the porous layer on the fluid structure and thermal performance using a so-called local thermal equilibrium energy model and local thermal non-equilibrium model. Their results show that, for low porosity medium, the use of porous medium is always beneficial as compared to a surface without porous medium regardless of the height of the porous medium. In addition, they also found that the presence of porous surface on the base heat transfer surface eliminate the second peak in distribution of local Nusselt number and thus improved temperature uniformity. However, the high porosity medium with small height gives lower heat transfer rates as compared to without porous medium. Among a relatively small number of experimental studies, Yakkatelli et al. [13] provided a visualization study of the flow dynamics of a single round jet impinging on aluminum foam. They found that an increase in jet Reynolds number or jet-exit-to-surface spacing helps the flow penetrate the porous media more evenly and reduces the exit of the porous foam. No heat transfer data were provided in their study. Another experimental study by Jeng and Tzeng [14] investigated convective heat transfer and pressure of forced convection in metallic porous (aluminum foam) block subject to a confined slot jet. Overall speaking, jet impinging into porous structures involves complex flow structures and heat transfer mechanisms. Existing literatures only addressed a small set of greatly simplified scenarios. More extensive studies are still warranted in this area.

A special type of structured-porous materials, made of highly conductive metallic wire mesh screens have garnered much renewed research interests for their capability to enhance heat transfer. Jacob [15] made reference to the use of a screen bonded to a heat transfer surface to promote boiling. He attributes the observed performance enhancement to the increase in surface area that the screen provided. Liu et al. [16] studied boiling of methanol and HFE-7100 on a surface covered with a single layer of mesh screen. They found that a 50-mesh layer enhances nucleate boiling only at lower superheats ($\leqslant$10 K) while a coarser, 10-mesh layer almost always lowers the heat transfer efficiency. Li and Peterson [17] investigated atmospheric pool boiling of water on horizontal copper screen laminate surfaces. They concluded that the increase in heat transfer surface area significantly enhanced performance. In a more comprehensive study, Wirtz and coworkers [18–20] studied boiling performance of wire mesh screen laminate extended surface matrices under various pool boiling and flow boiling conditions. They tested working fluids such as water, FC-72 and Isopentane. Boiling performance enhancements over plain surface were observed in all cases.

This literature review suggests that jet impingement on porous surfaces has not received much attention despite its potential superior heat transfer performance. In particular, experimental studies about structured-porous surfaces subjected to jet impingement cooling are very scare. In the present work, an experimental study of water jet impingement on a wire mesh screens coated surface and on a plain copper surface for comparison were performed. The potential heat transfer merits of combined jet impinging and wire mesh coated surface were evaluated. The effects of jet Reynolds number, jet inlet subcooling, and porous layer thickness on heat transfer performance were analyzed. In addition, surface ageing and data repeatability were also discussed.

2. Experimental

2.1. Test section

Fig. 1 shows a cross sectional view (cut at the symmetry plane) of the cylindrical test section, which includes the following major components: (1) a heat flux gauge, sintered on the top with layers of copper wire mesh screens, all made of oxygen-free copper; (2) a jet plate, made of high temperature, low thermal conductivity plastics; (3) a thick layer of thermal insulation made of high temperature fiberglass; and (4) a separate cylindrical heater section, also