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Research Paper

Evaporation/boiling heat transfer characteristics in an artery porous structure

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HIGHLIGHTS

- A novel artery porous structure was proposed to enhance the CHF of pool boiling.
- Unique evaporation/boiling curve for the artery porous structure was revealed.
- Maximum heat flux reached 416 W/cm^2 without the occurrence of any dryout.
- Liquid/vapor phase distribution and evolution were visually observed.
- Effects of pore size, artery depth and contact condition were investigated.

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ABSTRACT

Nucleate boiling is one of the most efficient and effective heat transfer modes, but is limited by the critical heat flux (CHF). An innovative artery porous structure was proposed in this work to enhance the CHF based on the concept of "phase separation and modulation" by forming individual flow paths for liquid supply and vapor venting while keeping the liquid/vapor interface located in the porous structure. In the experiment, the porous structure was made of sintered copper microparticles, multiple arteries were machined directly on the heated surface, and water was employed as the working fluid. The experimental results were compared with those on a flat surface, and a unique evaporation/boiling curve for the artery porous structure was revealed. The experiment validated the principle proposed here for CHF enhancement, and a maximum heat flux of 416 W/cm^2 on a heating area of 0.78 cm^2 was achieved without the occurrence of any dryout. Further increase of heat flux was limited only by the design temperature of the electrical heater, and a much higher CHF can be expected. In addition, the effects of pore size, artery depth and contact condition on the evaporation/boiling heat transfer performance in the artery porous structure were also experimentally investigated, which can guide further design optimizations of this novel structure.

1. Introduction

As one of the most efficient and effective heat transfer modes, nucleate boiling promises the attainment of a high heat flux, while still maintaining a relatively small superheat on the heating surface. As a result, it plays an important role in a variety of applications such as in the cooling of nuclear reactors, thermal management of high-power-density electronic devices, phase-change heat exchangers with various types as well as the refrigeration and air conditioning system [1–3]. However, the critical heat flux (CHF) is a limiting factor for the nucleate boiling, beyond which the temperature of the heating solid wall will increase sharply, resulting in a significant decrease in the surface heat flux. As the heat flux increases, more and more bubbles are generated, which coalesce to form "bubble mushrooms" and prevent the liquid from rewetting the heating surface. The direct resultant fact is that a thin vapor blanket completely enveloping the hot-spot forms a barrier to the heat transfer between the solid surface and the boiling fluid, which is also termed as boiling crisis [4]. A lower CHF value is undesirable in most systems as it would lead to the failure of nucleate boiling and the resultant very rapid burn-out of relevant devices to be cooled, which should be strictly avoided.

Nowadays for some special applications especially in some cutting-edge technology areas such as high power solid laser, advanced miniaturized high power electronics and advanced

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Nomenclature

D	diameter (m)
h	heat transfer coefficient (W/m^2 K)
H	height (m)
k	thermal conductivity (W/m K)
q	heat flux (W/m^2)
s	distance (m)
T	temperature (K)
ΔT	temperature difference (K)
W	width (m)

Greek symbols

σ	uncertainty
ρ	density (kg/m^3)
γ	evaporative latent heat (J/kg)

Subscripts

s	saturation
TC	thermocouple
v	vapor
w	wall

nuclear power reactors, the heat flux to be dissipated has reached several hundred Watts per square centimeter, which is far beyond the CHF of nucleate boiling with a conventional working fluid on a flat surface. It is essential to significantly enhance the CHF of nucleate boiling, which has become an important research topic in the subject of engineering thermophysics, and attracted the interest of quite a lot of researchers worldwide.

In the past two decades, a variety of methods have been proposed to enhance the CHF or heat transfer coefficient of nucleate boiling such as the employment of nanofluids [5–12], the addition of surfactant to the working fluid [13–17], the surface roughness/wettability modification by micro/nano fabrication technology [18–21] and the surface wettability modification by the coating technology [22–26], and a big progress has been made. In this work, we propose a novel artery porous structure to enhance the CHF of nucleate boiling, due to its easy fabrication, notable effect, good reliability as well as low cost, and previous studies related to the employment of a porous structure will be briefly reviewed below.

Early studies mostly focused on the employment of a porous structure with a uniform thickness. Li et al. [27–30] systematically investigated the evaporation/boiling heat transfer for a capillary structure with a range of wick thicknesses, volumetric porosities and mesh sizes under steady-state conditions. The capillary structure was made of multiple, uniform layers of sintered isotropic copper mesh, and an optimal sintering process was developed and employed to fabricate the capillary structure. This process minimized the interface contact thermal resistance between the heated wall and the capillary wick, as well as enhancing the contact conditions between the layers of copper mesh. Due to the effective reduction in the contact thermal resistance between the wall and capillary wick, both the evaporation/boiling heat transfer coefficient and the CHF demonstrated dramatic improvements, with heat transfer coefficients up to 245.5 kW/(m^2 K) and CHF values in excess of 367.9 W/cm^2, observed. The experimental results indicated that while the evaporation/boiling heat transfer coefficient, which increased with increasing heat flux, was only related to the exposed surface area but not the capillary wick thickness, the CHF was strongly dependent on the capillary wick thickness and increased proportionally with the increase of wick thickness. The experimental results also showed that the CHF was strongly dependent on both mesh size and volumetric porosity but the evaporation/boiling heat transfer coefficient was mainly affected by the mesh size. This study resulted in the development of a new evaporation/boiling curve for capillary wicking structures, which provided new physical insight into the unique nature of the evaporation/boiling process in these capillary wicking structures. Hwang et al. [31] experimentally examined the pool boiling on the thin uniform porous coatings using different copper particle diameters (between 40 and 80 μm), fabrications (loosely packed, shaken, or pressed), and particle characteristics (solid or porous particle) with coating thickness varying between 3 and 5 particle diameters. Experimental results showed that the CHF was enhanced to about 1.8 times for all the coatings, while the pre-CHF regime showed variations. The authors suggested that the presence of the thin uniform porous coating influenced the hydrodynamic (macroscale) stabilities such that the critical Rayleigh–Taylor wavelength decreased and/or the vapor area fraction increased in a manner to statistically cause a decrease in the dominant interfacial wavelength. Yang et al. [32] employed a set of copper foam pieces welded on the plain copper surface for pool boiling heat transfer enhancement. Water was used as the working fluid. The effects of pore size, foam cover thickness, and pool liquid temperatures were examined. Comparing to the plain surface, the superheat at the onset of nucleate boiling (ONB) was significantly decreased on copper foam covers and the heat transfer coefficients were two to three times higher. A large ppi (pores per inch) value provided more bubble nucleation sites and heat transfer area to enhance heat transfer, but generated large vapor release resistance to deteriorate the heat transfer. Therefore an optimal ppi value existed, which was determined as 60 ppi in this work. The effect of pool liquid temperature on the heat transfer enhancement depended on the ppi value. For small ppi value such as 30 ppi, lower pool liquid temperature can dissipate higher heat flux at the same wall superheat. However, the heat transfer performance was insensitive to the pool liquid temperatures when large ppi values such as 90 ppi were used. Weibel et al. [33] experimentally studied the evaporation/boiling heat transfer characteristics of a sintered copper powder wick surface. A novel test facility was developed, which fed the test fluid, i.e., water, to the wick by capillary action. This simulated the feeding mechanism with an actual heat pipe. Experiments with multiple samples, with thicknesses ranging from 600 to 1200 μm and particle sizes from 45 to 355 μm, demonstrated that for a given wick thickness, an optimum particle size existed which maximized the boiling heat transfer coefficient. The tests also showed that monoporous sintered wicks were able to support local heat fluxes of greater than 500 W/cm^2 without the occurrence of dryout. Additionally, in situ visualization of the wick surfaces during evaporation/boiling allowed the thermal performance to be correlated with the observed regimes. The sharp reduction in overall thermal resistance upon transition to a boiling regime was primarily attributable to the conductive resistance through the saturated wick material being bypassed.

Recent studies focused more on the application of the modulated (periodically non-uniform thickness) porous structures. Liter et al. [34] proposed the modulated (periodically non-uniform thickness) porous-layer coatings to enhance the pool-boiling CHF, which can separate the liquid and vapor phases, thus reducing the liquid/vapor counter flow resistance adjacent to the surface. Theories were suggested for two independent mechanisms capable of causing