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Enhanced critical heat flux with single-walled carbon nanotubes bonded on metal surfaces

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ABSTRACT

This study investigates a novel and practical technique to improve the critical heat flux (CHF) of thermal devices by bonding a film of single-walled carbon nanotubes (SWCNTs) to metal surfaces. Various SWCNT film layers in thicknesses of 296, 613, 845, and 1432 nm were fabricated by vacuum filtration. Experimental work of surface characterization and pool boiling heat transfer was conducted with bare stainless steel grade 316 heaters and SWCNT-coated heaters in the deionized water under atmospheric pressure. Surface characterization of the CNT adhesion showed that SWCNT adhesion to the metal surface exhibited properties of a smooth porous medium with smaller roughness compared to the bare SS316 substrate. Wall superheat and applied heat flux were measured and high speed images of boiling process were captured at a rate of 1500 frames/s during respective tests. The CHF with the random SWCNT network-coated heater was observed to increase by up to 55% compared to the bare SS316 heater. The increased porosity with the adhesion of a random SWCNT network is believed responsible for the enhanced CHF. However, nucleate boiling heat transfer coefficient with SWCNT-coated heaters was reduced compared to the bare heaters due to the lower surface roughness.

1. Introduction

1.1. General background

Thermal safety management is of importance for securing the safety and economy of thermal devices utilizing high power densities. For example, due to the presence of residual heat in a nuclear power reactor, a reactor vessel may experience potential thermal attacks from the decay heat accumulating inside the reactor vessel, and thus appropriate heat removal becomes a key objective to maintain the reactor vessel in a cooled state. Under improper transient conditions, physical penetration of the reactor by the molten material of nuclear fuels and structures is possible unless proper thermal and safety management is implemented. Thus, to delay and mitigate the potential thermal penetration, proper thermal safety management should be considered in terms of external vessel cooling on the outer vessel surface of the reactor [1]. The importance of thermal safety management is not limited to power reactor engineering, as the industrial fields of microchip cooling, computer cooling, boiling and refrigerating facilities, and thermal processors involving heat flow also require thermal management to secure the safety and sustainability of the integrated thermal devices and systems.

To develop methods to improve thermal safety management, a qualitative measure such as the thermal safety margin is required. Often, the critical heat flux (CHF) as a maximum applicable power density is utilized as the main parameter for determining the safety margin of a thermal system. The CHF is the upper limit of nucleate boiling heat transfer during a liquid–vapor phase change condition. If the CHF occurs, vapor blankets may form at the interface between the cooling fluid and heat transfer substrate, and subsequently the temperature of the substrate will rapidly increase by the order of 1000 °C in a few seconds. This thermal attack damages the physical integrity of the thermal devices and thus the maximum power input during normal and transient operations is strongly limited to a value below the CHF. Therefore, research related to the enhancement of CHF in boiling heat transfer processes is important to improve the thermal safety margin in the related industrial fields.

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1.2. Carbon nanotubes for thermal management

During the past decade, there has been an evolutionary progress in the application of nanostructures in the fields of material sciences and chemical engineering. The one-dimensionally confined nanostructures from various materials, such as silicon, metal, organic, and inorganic materials, have been strong candidates to modify existing applications in various scientific and engineering fields due to the enhanced properties from quantum confinement effects. Among the many materials invented, the application of carbon nanotubes (CNTs) [2] has been investigated by many researchers due to their excellent thermo-physical properties and inert chemistry, in conjunction with a flexible application range feasible for many industrial practices including the field of thermal applications. Berber et al. [3] and Che et al. [4] investigated the enhanced thermal conductivity of CNTs through theoretical studies. Kim et al. [5], Choi et al. [6], and Aliev et al. [7] observed enhanced thermal conductivity of individually aligned multi-walled carbon nanotubes (MWCNTs) through laboratory experiments, and Pop et al. [8] and Dresselhaus and Eklund [9] investigated conductivity in single-walled carbon nanotubes (SWCNTs). Other reports have shown that vertically-aligned CNT arrays could have highly anisotropic thermal conductivities between the aligned direction and the orthogonal direction. [10] The unique thermal properties of CNTs make them potentially useful in thermal systems, such as solid state thermal rectifiers [11], transparent thin film heaters [12], fillers for high thermal conductivity polymers [13], thermopower applications [14], and microchip cooling devices [15].

1.3. Literature reports of pool boiling CHF enhancement using CNT adhesion

In view of thermal management, the application of CNTs is expected to be very advantageous for delaying localized high heat flux and temperature. Despite its usefulness, however, only a few studies have been conducted on the effect of CNT adhesion on thermal devices applicable for pool boiling of water. When CNTs are introduced to ordinary metal substrates, they tend to form a porous medium, which complicates the interpretation of the phase-change heat transfer phenomena. According to the kinetic limit, the theoretical pool boiling CHF of water achievable with a flat plate heater under ideal conditions could be as high as 80 MW/m^2 for pentane as a working fluid [16]. Significant efforts have been made in an attempt to understand the theoretical and practical limits using the enhanced surface modification. Liter and Kaviany [16] investigated this practical limit by investigating the enhancement of the CHF through the use of porous media. They developed a model for pool boiling CHF enhancement by use of a modulated porous layer coating. The achievable CHF enhancement could be predicted by the modulation of the two-phase flow and the results could not achieve the theoretical limit. According to Zuber's hydrodynamic instability theory [17], the CHF is predicted when the speed of vapor departure reaches the critical vapor velocity, and typical value of the reported CHF is approximately 1 MW/m^2 without surface modification of the plain metal substrate. However, enhanced CHF could be achieved with the application of porous media, either by nanofluids boiling or coating techniques, though the enhancement is often widely varied from <10% to as much as 200% compared to the base fluid and untreated heaters [18,19].

An interesting finding with nanofluids boiling is the in situ surface modification by the deposition of nanoparticles in microcavities of the heat transfer surface during the nucleate boiling phase, which causes a significant change in the surface characteristics. The change in wettability has been reported as the most significant parameter in explaining the consequential findings of enhanced CHF [18]. More recent reports in the literature have focused on understanding surface modification effects including wettability, porosity, roughness, and changes in thermal properties [20–22]. Shanbedi et al. [23] investigated heat transfer characteristics of ethylenediamine (EDA) MWCNTs dispersed in water in a two-phase closed thermosyphon. The results showed that the reduced thermal resistance of the EDA–MWCNT nanofluids resulted in an increase in the thermal efficiency of the thermosyphon. Azizi et al. [24] performed a similar experiment with a different nanofluid of graphene/water, and a porous medium formed as a consequence of nanofluids boiling. The formation of the porous layer is in alignment with the deposition of the nanoparticles [19], and this often improves the capillary wicking or surface wettability [18].

The application of nanofluids shows some practical limitations in terms of chemistry control, mechanical erosion, and sedimentation, which increases the overall cost of the thermal process. However, pretreatment of nanoparticles or CNTs on the thermal device may be beneficial in reducing the operational cost and eliminating the management difficulty. Several studies have reported enhanced thermal performance of CNT coatings in dielectric fluids and ordinary water [25–30]. A general trend observed is that CNT growth on the plain substrate of either a semiconductor or metal plates tends to make the surface porous. Using this CNT growth, some studies report the simultaneous enhancement in the nucleate boiling heat transfer coefficient and CHF due to the enhanced capillary wicking structure. The enhancement in the heat transfer coefficient has been attributed to increases in nucleate site density, increases in exposed surface area, and enlarged bubble departure diameters due to the porous wicking structure. Improvements in CHF have been explained in terms of the reduced permeability and capillary pressure due to the wicking structure formed by dense CNTs. Although seen very rarely, Launay et al. [30] report no CHF enhancement with CNTs coatings on Si substrates compared to CHF with bare Si substrates, and this was attributed to increased thermal resistance between the substrate wall and the CNTs. Table 1 summarizes the studies of pool boiling heat transfer performed with CNTs coating and key characteristics of CNTs adhesion used in the current study.

1.4. Objectives of study

Our interests relate to the application of a random SWCNT network on stainless steel alloys with a working fluid of water. The thermal management system using nanomaterials and nanostructures have critical barriers to practical applications of pool boiling heat transfer. The nanofluids can enhance CHF, but it is difficult to maintain a consistent surface condition due to the continuous precipitation of nanoparticles. In addition, the aligned nanostructured surfaces have been strong candidates to enhance the heat transfer characteristics and elucidate the working principle of boiling heat transfer in various surface conditions [31–34]. However, nanostructures such as vertically aligned CNTs and nanowire arrays are not able to maintain their intrinsically aligned arrangements during the boiling process because of damage to the fine structures. In addition, the fabrication of aligned nanostructure arrays on the surface would require a high-cost manufacturing process including high temperature processes.

In this study, we fabricated the nanostructured surface using a random SWCNT network film on a metal surface for high power heat transfer applications. This was accomplished by a simple solution processing method without the need for a high temperature process, and the application of the nanostructured surface to enhancing the pool boiling CHF was investigated under atmospheric pressure. As discussed in the previous section, only a few studies [25–30] report on the thermal performance of CNT coatings with various substrates. However, no studies have investigated stainless steel alloy as a substrate, which may have practical use