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Boiling heat transfer enhancement with stable nanofluids and laser textured copper surfaces

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ABSTRACT

The rate of heat removal is an important factor which influences the efficiency of industrial processes. Due to this reason, methods to improve it is an active research topic. Of particular interest to the current study is the boiling heat transfer process which can potentially be enhanced by the use of nanofluids and textured surfaces. Even though many studies have been conducted to determine the heat transfer ability of nanofluids, controversy exists in the results published so far. We gathered from the literature that the stability of nanofluids used in these works was not reported. Therefore, in this article, we analyzed the effect of nanofluid stability on boiling heat transfer using nanofluids of varying stability. Nanofluids prepared by dispersing functionalized multi-wall carbon nanotubes in ethanol remained stable even after boiling. We confirmed the stability of these nanofluids by comparing the mean particle size of freshly prepared and boiled samples by dynamic light scattering. Conversely, the aqueous nanofluids prepared using functionalized or non-functionalized nanotubes with and without the aid of surfactants, destabilized instantly when boiled. To test the effect of nanofluid stability on boiling heat transfer, we employed each of these nanofluids, and the base liquids ethanol and water to cool a polished heated copper disc. Interestingly, we found that only stable nanofluids cooled the disc faster compared to the base liquid. Since stable nanofluids were shown to enhance boiling heat transfer, we studied the effect of combining stable nanofluids with micro-nanoscale textured metal surfaces. Femtosecond laser micromachining was used to produce laser induced periodic structures and laser inscribed square pillar structures on copper discs, of which the surface morphology was checked using 3D confocal microscopy. We observed a 59% enhancement in the boiling heat transfer rate when stable ethanol based multi-wall carbon nanotube nanofluids were used to cool discs with laser inscribed square pillar texture.

1. Introduction

The requirement of increased and rapid heat removal is of interest since it is one of the significant limitations in improving the processing speed of machines and efficiency of industrial processes. One of the recently developed methods to improve heat transfer is by the addition of solid particles to traditional heat transfer fluids [1,2]. The addition of solid particles to the host heat transfer fluids is being explored, as it is well-known that the thermal conductivity of solids is much higher than that of liquids. For instance, the thermal conductivity of copper is 700 times and the one for carbon nanotubes is approximately 5000 times higher than the thermal conductivity of water [3].

The idea of incorporating solid particles into liquids to improve their thermal conductivity was proposed by Sir Maxwell back in the 1800 s [4]. When experimenters prepared new coolants by adding micrometer-sized solid particles in liquids, they faced the issue of particles clogging the heat transfer flow channels. The development of nanometer-sized particles served as a motivation to prepare nanofluids, which are colloidal dispersions of carbon nanotubes, metal or metal oxide nanoparticles in a host fluid such as water or organic solvents [1]. Over the last two decades, considerable effort was invested to investigate the thermal behavior of nanofluids. Different levels of heat transfer enhancement of aqueous nanofluids were reported in various review articles [5–8] while other researchers reported deterioration of heat transfer with nanofluids [9]. Deterioration of the heat transfer enhancement associated with nanofluid shelf time was also reported by several research groups [2,10]. Unfortunately, we too often notice that the stability of nanofluid samples used in most experiments is

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not reported. In most cases, the nanofluid samples are ultrasonicated before conducting the tests to produce a visibly stable dispersion, but the beneficial effect of well-dispersed nanoparticles rapidly deteriorates after preparation. We speculate that the agglomeration of nanoparticles and settling out of dispersion during storage or heating could be the reason for the contradictory results reported in the literature.

It was initially thought that nanoparticles would not settle out of dispersion due to their small size and the incessant Brownian motion [11]. However, the van der Waals force between nanoparticles causes them to agglomerate and leads to settling of the newly-formed larger particle agglomerates out of dispersion. To prevent the nanoparticles from agglomerating, surfactants have been (and are) used in most of the experimental works published in the literature [12]. The disadvantage with surfactant stabilization is that typical surfactants degrade at temperatures higher than 60 °C, leading to the destabilization of nanofluids when heated [13]. It was also pointed out in a recent review article that particle migration could be the reason for the deterioration of properties [14]. Thus, we understand that despite the significant amount of research reported with nanofluids, its long-term stability remains a challenge.

Surface modification of nanoparticles is essential to prevent agglomeration when dispersed in a base liquid. Surface modification of nanoparticles was mostly attempted by wet chemistry, but the difficulty in removing chemicals from the nanofluids after synthesis is a significant disadvantage of this method [15]. Recently, investigators from our laboratory (Plasma Processing Laboratory) added oxygen-containing functional groups on multi-wall carbon nanotubes (MWCNTs) by plasma functionalization [16]. The nanofluids prepared by dispersing such functionalized nanotubes in water and ethylene glycol have been reported to remain stable for more than eight years when stored in glass vials and when heated to temperatures higher than the surfactant degradation limit [17]. Another constraining aspect that we were the first to report on is the effect of heat exchanger material on the stability of the nanofluid, since metal ions released from the structure may destabilize it. In our recent article, we reported that water and ethylene glycol based nanofluids destabilize, whereas ethanol based nanofluid containing functionalized carbon nanotubes remain stable in the presence of several metals (such as copper, stainless steel, titanium and carbon steel) and even after it was boiled [18].

Going back to literature, almost all heat transfer studies with nanofluids attributed the observed boiling heat transfer enhancement to the increase in surface roughness caused by the nanoparticle agglomerates deposited on the heater surface [19–21]. The effects of surface texturing on boiling heat transfer have been studied extensively. Jakob and Fritz reported one of the first studies on the effect of surface polish on boiling of water in 1931, in which they observed an increase in the heat transfer coefficient with rougher surfaces compared to polished ones [22]. Clark et al. observed that scratches and pits on the heater surface served as active nucleation sites for bubble formation [23]. This observation led to the development of creating nucleation sites artificially and also to understand the effect of cavity size on boiling [24]. Gottzmann's group observed an increase in boiling heat transfer by depositing sintered metal particles on the surface of heater tubes [25]. Various studies that introduced different microstructures, reentrant pits and microgrooves on the heater surfaces reported an increase in boiling heat transfer as well [26]. Different structuring techniques such as polymer coatings, photolithography, coatings with nanorods or nanoparticles, anodic oxidation, and integrating surface structures as micropins and channels were tried to vary surface texture for boiling heat transfer applications [27–30]. Kruse et al. reported an increase in pool boiling heat transfer using laser textured stainless steel surfaces with micro-nano dual scale roughness structures created by laser micromachining [31]. Rahman et al. observed heat transfer increase with dual scale roughness surface prepared by coating a Tobacco mosaic virus-grown surface with nickel and PTFE coatings [32]. The frequency of vapor bubble evolution, the speed of rewetting dry spots on a heater surface, and nucleation site density are all important factors that affect boiling heat transfer.

However, very few studies have reported the impact of surface textures with nanoscale roughness on boiling heat transfer. The reported studies used either nanowire or nanorod structure prepared by electrodeposition or atomic deposition techniques [29,33]. Even though surface textures fabricated by such techniques are called 'nanostructured', they actually contain microdefects due to artifacts of the deposition techniques, and end up being dual roughness structure [29]. Since the availability of such microdefects is dependent on the degree of flatness of the substrate achieved by polishing, we presume that the production of dual surface structure is random and unpredictable by such processes. Evaluating the above-mentioned surface modification techniques we comprehend that laser micromachining is a less complex, single-step process to produce textured surfaces compared to coating and thin film deposition methods which involve different steps and a clean room environment [34]. Therefore, we chose femtosecond laser micromachining to prepare periodic nanoscale and dual scale roughness structures on copper and investigated their influence on boiling heat transfer enhancement.

In this article, we first analyzed the effect of nanofluid stability on boiling heat transfer, for which we prepared stable and unstable nanofluids. We then studied the effect of surface texture on boiling heat transfer when these surfaces are combined with stable nanofluids.

2. Materials and methods

2.1. Preparation of nanofluids

Hordy et al. developed the method of preparing stable nanofluids in our laboratory using plasma functionalized multi-walled carbon nanotubes (F-MWCNTs) in water and ethylene glycol [16]. We used this method to prepare stable water- and ethanol-based F-MWCNT nanofluids. Multi-walled carbon nanotubes are grown on a stainless steel (SS-316) mesh in a chemical vapor deposition furnace. After cleaning the mesh by sonicating in acetone for 15 min, it is placed in a ceramic boat and inserted into the furnace heated to 700 °C in an argon atmosphere. The mesh is heated for 5 min, and then acetylene gas (the carbon source) is injected at 68 sccm for 2 min. The mesh is then left in the furnace for a growth time of 2 min. The carbon nanotube covered SS mesh is taken out of the furnace after the growth period and transferred to the plasma reactor. A low-pressure, capacitively-coupled, radio-frequency (13.56 MHz) plasma system with the gas mixture Ar/O_2/C_2H_6:250/5/1 (sccm), at a power of 20 W (electrode diameter 10 cm) is used to functionalize the MWCNT-covered mesh for 5 min. The oxygen functionalized MWCNTs on the SS mesh are then dispersed in two different base liquids, water (reverse osmosis treated) and ethanol (99% anhydrous), by ultrasonication during which the F-MWCNTs are broken off without being uprooted, hence preventing the mesh material from entering the nanofluid. Dispersing the functionalized and non-functionalized MWCNTs in ethanol, water and water with surfactant, we prepared nanofluids of varying stability (80 ppm MWCNT concentration). Aqueous nanofluids containing non-functionalized MWCNTs (NF-W) destabilize in less than one day from preparation. We used 500 and 800 ppm of surfactant sodium dodecyl sulfate to prepare