



Experimental study on critical heat flux of highly efficient soft hydrophilic CuO–chitosan nanofluid templates



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ABSTRACT

Nanofluids (NFs) are highly promising liquids for critical heat flux (CHF) enhancement in pool boiling, due to their environmental friendliness, easy chemical modification, tunability, low cost, and high thermal conductivity (TC). NFs based on CuO nanoparticles (NPs) are moderately good for CHF applications, but have low TC compared with other metal-oxide NFs. The development of ecofriendly NFs with enhanced thermal transfer properties is essential. In this study, we engineered a highly efficient, soft, hydrophilic CuO–chitosan (CS) NF template, the first of its kind. CS is a low-cost, naturally abundant, raw material, with hydroxyl, amine, and amide functional groups. When combined with CuO NPs, the CS functional groups create strong CuO–CS nanocomposites (CuO–CS NCs). In this research, 0.003, 0.006, 0.03 and 0.06-wt% CuO–CS NFs were produced by dissolving various concentrations of the CuO–CS NC in deionized water. A nichrome wire was coated with the NF samples during pool boiling experiments. The 0.06-wt% CuO–CS NF showed the highest CHF value, approaching 79%, which is much higher than that of pristine CuO NPs (28%). The chemical structure and crystallinity of the CuO–CS NCs were investigated using Fourier-transform infrared and X-ray photoelectron spectroscopy and X-ray diffraction; zeta potential and zeta size analyses were used to determine their charge, shape, and size. Atomic force microscopy, field-emission scanning electron microscopy, and transmission electron microscopy of the CuO–CS NC-coated nichrome wire after pool boiling experiments revealed a rough surface with high wettability and a low contact angle (42° for the 0.06-wt% CuO–CS NF sample), due to the formation of a nanoporous, soft template on the wire surface. We also demonstrated a method for *in situ* production of a naturally available, sustainably green, biodegradable raw material. The robust CuO–CS NF introduced here is expected to enhance pool boiling CHF, even at the lowest concentrations (0.003 wt%) required for practical applications.

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1. Introduction

Nanomaterials have been studied extensively due to their promising applications in various fields. Energy-harvesting technologies at the nanoscale level, using naturally existing materials, are highly desirable for sustainable green-energy practices. Nanofluids (NFs), introduced in 1995 by Choi [1] (Argonne National Laboratory), have occupied a vital role in industrial practices in the restoration of natural energy levels [2], and they continue to advance development in emerging coolant technologies [3] for solar energy, heat exchanger, nuclear reactor, automotive, and electronic cooling applications [4]. NFs, created by dispersing

metal-oxide nanoparticles (NPs) (microgram to milligram scale) in a suitable solvent system (the base fluid), display superior thermal conductivity (TC) for critical heat flux (CHF) enhancement [5]. Additionally, NFs provide effective heat transfer and chemical stability, while minimizing cooling system corrosion that includes chemical stability and effective boiling point. To date, various metal-oxide NFs (e.g., Al₂O₃, TiO₂, ZnO, Fe₃O₄, SiO₂, CuO and carbon materials) have been used to increase the CHF [6,7]. However, these NFs have significant drawbacks, which include the need for high volume concentrations and a short shelf-life due to decomposition, scaling, and/or clogging. Many are not environmentally suitable. Additionally, the redox potential of NFs during CHF have resulted in surface corrosion in some cases. Thus, a high-performance, low-cost, environmentally benign, highly hydrophilic nanohybrid composite is needed to increase the CHF value.

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Recently, chitosan (CS) has attracted much attention owing to its many active functional groups (hydroxyls, amides, and free amine groups), as well as its uniform, geometrically flat template structure and high TC. CS is a nontoxic, linear cationic, biodegradable, biocompatible polysaccharide that can be obtained from the deacetylation of chitin. CS offers numerous advantages [8–11]. Phuoc et al. discussed the viscosity and TC of NFs created using multi-walled carbon nanotubes stabilized by CS; the TC of pure CS is 0.581 W/mK, and it is relatively good value compared with deionized (DI) water (0.571 W/mK) [9]. CS has also demonstrated an ultra-high adsorption capacity ($\sim 1000\text{--}1100\text{ g/kg}^{-15}$) for contaminant removal from water, outperforming activated carbon. A multifunctional CS-copper-oxide hybrid material was studied by Haldorai et al. [12] for its photocatalytic and antibacterial properties. Gouda et al. [13] synthesized CuO–CS nanocomposites (NCs) for antibacterial cotton fabric finishing; excellent antibacterial activity was demonstrated by the fabric.

From fundamental and practical standpoints, it is important to understand how water wets the free-standing CS surface. CS dissolves readily in DI water, due to the availability of hydroxyl and amine functional groups on the surface of CS templates. These functional groups support strong hydrogen bonds between CS and the water molecules and also provide CS with superior adsorption properties for contaminants via the formation of coordination bonds. Entrapped metal-oxide NPs in supporting CS nanomaterials have many important technological benefits, in particular, water harvesting in two-phase heat-transfer processes, such as condensation and pool boiling. The high hydrophilic nature and strong chelating behavior of CS towards metal oxides prompted our investigation of its application to CHF enhancement in pool boiling and the development of a high-performance NF using a CS-like biopolymer.

The purpose of this study was to maximize the pool boiling CHF of NFs by introducing a novel NC material due to use of high wt% of CuO NPs and their practical applications are limited [14–17]. Specifically, we developed a new NC made from CuO anchored with CS (CuO–CS). The anchoring of CuO onto the amine and hydroxyl groups of CS nanotemplates (via coordinate-covalent bonds) extended the CHF and enhanced TC, compared with pure CuO NPs. In this research, 0.003, 0.006, 0.03 and 0.06-wt% CuO–CS NFs were produced by dissolving a CuO–CS NC in DI water. A nichrome wire was coated with the NF samples during pool boiling experiments.

The size and charge of CuO, CS, and CuO–CS NCs were characterized using particle size analysis and zeta potential measurements. Fourier-transform infrared (FTIR) and X-ray photoelectron (XPS) spectra revealed the structure and functionality of the CuO NPs, CS, and their atomic level interactions in the CuO–CS NC formation; the crystallinity of the CuO NPs, CS NPs, and CuO–CS NCs were confirmed by X-ray diffraction (XRD). The thermal stability of CS NPs and CuO–CS NCs were determined by thermogravimetric analysis (TGA). Transmission electron microscopy (TEM) images revealed the structure and morphology of CuO NPs, CS NPs, and CuO–CS NCs.

The soft nanotemplate build-up on the nichrome wire surface and its average surface roughness (R_a) were investigated using field-emission scanning electron microscopy (FE-SEM) and atomic force microscopy (AFM). Surface roughness creates nanoscale cavities that affect nucleation during boiling heat transfer; thus, the heat transfer efficiency is proportional to the surface roughness. These cavities also act as starting sites for heterogeneous liquid nucleation and bubble formation [18]. The growth and departure of bubbles significantly influences the CHF. Between the CS templates, we observed a three-dimensional (3D) CuO core-shell-like nanostructure, created by chelation. The lowest contact angle (CA) and highest wettability were observed for the developed

CuO–CS nanotemplates, which were formed by the deposition of CuO–CS NCs onto a nichrome wire [19]. All of the CuO–CS NF samples showed a higher TC in DI water. An enhanced CHF value of nearly 79% was observed for the 0.06-wt% CuO–CS NF, which is significantly higher than that of CuO NFs (28%). There have been a few reports on the synthesis of CuO/CS for biological applications [12,13]. To our knowledge, this is the first demonstration of enhanced pool boiling heat transfer and wettability using a highly efficient, soft, hydrophilic CuO–CS NF template.

2. Experimental

2.1. Materials

All chemicals were used as purchased, without further purification. Chitosan (CS) (low molecular weight, with a 75% degree of deacetylation), $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (99.98%), ascorbic acid (99.0%), hydrazine (N_2H_4 , 98.0%), and NaOH (99.0%) were supplied by Sigma Aldrich (South Korea). Double distilled water was used throughout the experiments.

2.2. Preparation of CuO–CS nano composites (NCs)

Cu NPs were synthesized using a modified version of the method described by Usman et al. [20]. A blue-colored aqueous solution was created by dissolving 0.4 g of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ in double-distilled water (10 mL). This solution was then added dropwise to a 0.1-M acetic acid solution containing 40 mL of CS; the color of the solution changed from blue to light blue. After stirring and refluxing at 120 °C for 20 min, 0.5 mL of 0.05-M ascorbic acid was added to the solution. The solution was stirred for an additional 20 min before adding 2 mL of 0.6-M NaOH; no immediate color change was observed after this addition. However, after stirring for 30 min, the solution turned light green. N_2H_4 (0.5 mL) was then added, which resulted in a brown coloration before changing to dark red after 5 min of stirring. The solution was stirred for an additional 30 min to allow the reaction to reach completion. The reaction mixture was allowed to cool to room temperature. The solution was then centrifuged at 14,000 rpm for 15 min to obtain the CuO–CS NCs once the supernatant was discarded. The particles were washed repeatedly to ensure purity.

2.3. CuO–CS NF zeta potential and thermal conductivity (TC) measurements

Zeta potential measurements were performed using 0.06-wt% CuO–NP NF, and CuO–CS NFs. The measurement was run at 10 V, 25 °C, with a switch time of 20 s. The transient hot wire (THW) method was used to determine the TC of the CuO–CS NF; the rise in the temperature of the hot wire is related to the TC (k) of the fluid. Details regarding the THW technique are provided in the following section.

2.4. Pool boiling experimental apparatus setup and procedure

A schematic illustration of the experimental apparatus is shown in Fig. 1. The apparatus consisted of a rectangle vessel, a Teflon cover, a reflux condenser to maintain the volume concentration of the working fluid during boiling, two copper electrodes, and a power supply. A horizontally fixed NiCr wire was fixed between two copper electrodes. The voltage, current, and temperature signals were collected by a data acquisition system (DAQ). The experiments were conducted in a stabilized atmosphere at a saturated temperature of about 100 °C. Power was supplied to the wire heater until the CHF was reached. The power was increased gradually

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