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Pool boiling heat transfer to dilute copper oxide aqueous nanofluids

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ABSTRACT

A set of experiments have been performed to quantify the pool boiling heat transfer coefficient of dilute copper oxide water-based nanofluids at mass concentrations of 0.1–0.4%. To stabilize the two-step nanofluids, pH control, stirring and sonication were utilized. For investigating the influence of surfactant as a surface active agent additive on the pool boiling heat transfer coefficient of nanofluids, SDS, SDBS and Triton X-100 were used. Influence of some operating parameters such as applied heat flux, mass concentration of nanofluids and other parameters such as roughness of surface, boiling contact angle and deposition on the pool boiling heat transfer coefficient of nanofluids were experimentally investigated. Results demonstrated a significant deterioration of heat transfer coefficient of nanofluids comparing with the base fluid in the absence of surfactants, however, in the presence of surfactant, higher pool boiling heat transfer coefficient was reported. According to results, roughness of surface is strongly controlled by nanofluid concentration due to deposition of nanofluids on the heating section. Rectilinear changes of deposition with time in term of fouling resistance were seen at both regions with natural convection and nucleate boiling dominant heat transfer mechanisms.

1. Introduction

Boiling heat transfer is one of the major interests of heat transfer experts, not because of the complexity of boiling phenomena, but also its utilizations in heating/cooling systems and industrial processes and its applications in refrigeration, power generation, heat exchangers, cooling of high-power electronics components and PWR nuclear reactors. Removing a large quantities of heat in the least possible compact size has always been a key point for designing the heat exchanging media. Thus, enhancing the heat transfer coefficient and thermal efficiency of above-mentioned systems is indispensable and vital. Pool boiling involves all the interactive, but complicated, and dynamic processes such as hydrodynamics, heat and mass transfer (particularly in multi-component mixtures) and sub-phenomena such as: nucleation, bubble coalescence, and collapse of bubbles. Many efforts have been made to experimentally investigate on the pool boiling heat transfer of different fluids including: pure liquids, multi-component mixtures, refrigerants and none-Newtonian fluids. However, a simple statistical search among the published documents reveals this fact that nanofluid-related documents are less in number when comparing to other pool boiling subjects. As can be seen in Fig. 1, more researches should be conducted in context of understanding the heat transfer characteristics of nanofluids. A brief literature review on the pool boiling heat transfer of nanofluids has been represented in the following section.

2. Literature review

For the first time in 1995, Choi introduced the concept of nanofluid in his investigations [1]. He provided results of a theoretical study of suspended copper nanoparticles in a base fluid and demonstrated significant improvement in thermal properties of the test colloid fluid. Further experimental investigations have reported that suspensions containing nanoparticles have substantially higher thermal conductivities than traditional heat transfer fluids [2–4]. Recently, Xuan summarized the main factors belonging to nanofluids that enhance heat transfer as follows [5]:

(a) The nanoparticles can increase the surface area; (b) nanoparticles have higher interaction and collisions among the particles and fluid in comparison with other solid particles (e.g. microparticles); and (c) increased mixing fluctuation and turbulence of the fluid. Owing to these attributes, it is expected that the heat transfer performance of water, the most widely used coolant, can

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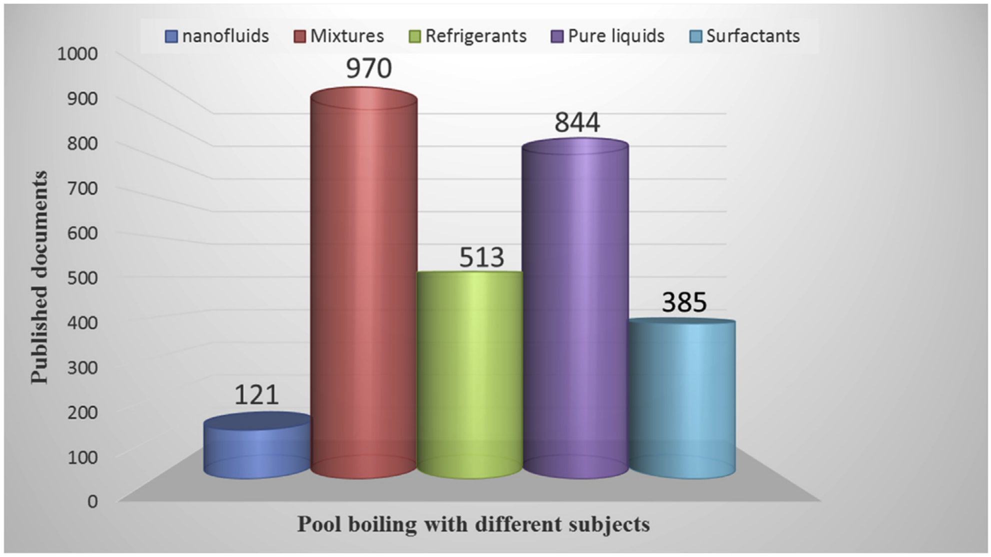

Fig. 1. Proportion of conducted researches on boiling in terms of different subjects; investigations on nanofluid after several decades are still less in number; (Direct keywords in www.sciencedirect.com).

be improved [6]. Although many researchers such as Das [7] showed that the boiling heat transfer performance deteriorates when nanofluid is used as working fluid, but there are still controversial reports that nanofluids can enhance the boiling performance [8]. Lui et al. [9] conducted an experimental investigation on boiling of CuO/water nanofluids around the grooved copper block and reported the enhancement of pool boiling heat transfer coefficient close to 50%. Shi et al. [10] and Tu et al. [11] performed experiments on Al_2O_3 nanofluids and collected set of experimental data that when compared to base fluid, demonstrated enhancement up to 64%. Wen et al. [12] represented the significant enhancement of heat transfer coefficient of TiO_2/water and Al_2O_3/water nanofluids on the stainless steel cylinder with diameter of 150 mm. Witharana [13], Troung [14], Ahn et al. [15] and Sarafraz et al. [16,17] demonstrated the enhancement of pool boiling heat transfer coefficient using nanofluids on heaters with different geometrical properties. More information can be found on cited references. In contrast, many investigators demonstrated the reduction of pool boiling heat transfer coefficient in their results. Coursey and Kim [18], Bang and Chang [19] and Sajith [20] carried some experiments out to investigate the effect of Al_2O_3 water based nanofluids on pool boiling heat transfer coefficient. They also surveyed the influence of scale formation and particle deposition around the heating section. The outstanding point of their works was to show the deterioration of heat transfer coefficient. Kim et al. [21], conducted a research based on the boiling heat transfer of Al_2O_3, CuO ZrO_2 and SiO_2 water based nanofluid on a wire with diameter about 0.38 mm and showed the significant deterioration of heat transfer coefficient due to the scale formation. Chopkar et al. [22], Kim et al. [23], Narayan et al. [24], You et al. [25] and Vassallo et al. [26] performed studies on boiling of nanofluid and small change in heat transfer coefficient was reported. As can be seen in the above-mentioned, controversial reports on boiling of nanofluids may be found in literature. Briefly speaking, Nanofluid pool boiling literature is in conflict over whether nanoparticles can enhance or degrade boiling heat transfer.

In the present work, CuO/water nanofluids are prepared using two-step method and stabilized using pH control, stirring, and sonication processes. By employing these methods, stability of nanofluids can be improved up to 1080hr. Pool boiling heat transfer coefficients of nanofluids, in the absence/presence of SDS, SDBS surfactants at the same mass concentration (0.1%) are experimentally measured. Influence of surfactants on the bubble-surface contact angle and bubble formation rate is visually investigated and briefly discussed. Likewise, influence of particle deposition on the heater roughness is experimentally investigated and interesting results regarding to scale formation and roughness in term of fouling resistance is represented.

3. Experimental

3.1. Experimental apparatus and procedure

This study focuses on the nucleate pool boiling of nanofluids on the surface of a horizontal cylindrical heater. A schematic of test facility has been shown in Fig. 2a.

As can be seen in Fig. 2a, experimental setup consists of three main sections: measurement instruments, boiling test section and photographic system. The stainless steel vessel is equipped with the boiling test section and condenser. The condenser (which is constantly cooled by water/ethylene glycol cooling cycle) condenses the vapor produced by the applied heat and the condensed liquid is returned back to the bottom of the vessel for re-evaporation. A pressure sensor is mounted on top of the vessel to control the pressure of test vessel equals to the atmospheric pressure throughout the experiment. The whole system is heavily insulated for more controllability and reduction of heat loss. The temperature of the liquid inside the test vessel is monitored and controlled at predetermined set point by a thermal regulator which involves eight of PT-100Ω thermometers and appropriate vertical auxiliary heater. These RTDs are used to measure the bulk liquid temperature during experiments mounted at different locations inside the test vessel (bottom, up, left, right, center and four around the heating section). Heating section can be considered as the most important section of the test apparatus. A horizontal stainless steel cylinder with outer diameter of 21 mm and length of 350 mm that only the first 105 mm of its length is internally heated using a bolt heater (manufactured by Cetal Co.). It is also equipped with eight K-type calibrated thermocouples, embedded along the circumference of the rod, very close to the heating surface. The arithmetic average of these eight thermocouples can be considered as the surface temperature. A PC-based