International Journal of Heat and Mass Transfer 109 (2017) 157–166

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The effect of nanoparticle type and nanoparticle mass fraction on heat transfer enhancement in pool boiling

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ARTICLE INFO

Article history:
Received 4 April 2016
Received in revised form 19 January 2017
Accepted 30 January 2017

Keywords:
Pool boiling heat transfer
Nanofluids
Titanium oxide nanoparticles
Copper oxide nanoparticles
Heat transfer enhancement

ABSTRACT

Determining the heat transfer performance with nanofluids is of cardinal importance in the utilization of nanofluids in thermal systems. This study presents an experimental investigation on nucleate pool boiling heat transfer of TiO_2 nanoparticles/water and CuO nanoparticles/water nanofluids on a flat heater plate and aims to reveal the effect of mass fraction of nanoparticles in these nanofluids for attaining the maximum enhancement in pool boiling heat transfer. The effect of mass fraction on boiling heat transfer characteristics was studied for mass fractions varying from 0.001% to 0.2% for the heat flux range between 48.7 and 134.9 kW/m^2. The experimental results showed that the heat transfer performance was improved when TiO_2 nanoparticles were added to pure water, as base fluid. However, the amount of enhancement was highly dependent on mass fraction. It was realized that the lowest mass fraction (0.001%), namely the dilute TiO_2 nanoparticles/water nanofluid, has the largest enhancement (around 15%). A further increase in mass fraction still augments heat transfer compared to pure water, however, the amount of enhancement decreased with mass fraction. Furthermore, the performed visualization showed that the addition of nanoparticles into the base fluid, increased the number of nucleation sites, and the bubbles had a more spherical shape along with a decrease in their size. For CuO/water nanofluids, heat transfer was enhanced at mass fractions larger than 0.001%. This enhancement could be more than 35% for the mass fraction of 0.2 wt.%. This study clearly indicates that the nanoparticle mass fraction corresponding to the best performance is highly dependent on the type of nanoparticle.

1. Introduction

Heat transfer performance of many industrial processes can be improved further by using new approaches, materials and fluids to eventually help the energy efficiency and eventual economic and environmental benefits. As a result of growing research efforts, enhancements in the performance are viable with enhanced micro-and nano structured surfaces [1–4] or working fluids with different surfactants or polymeric solutions [5,6].

Another possible method for modifying working fluids is implemented through dispersions of metallic and/or non-metallic, commonly metal-oxide, nanoparticles with higher thermal conductivities and size range of 1–100 nm, in conventional base fluids such as water, ethylene glycol, engine oil, propylene glycol, refrigerants and/or proper mixture of above-mentioned fluids [7]. Resulting nanofluids as alternative working fluids could significantly enhance heat transfer and thus have attracted much attention of many researchers around the world. Such fluids have found applications in thermal systems such as solar energy systems [8], heat exchangers [9], domestic refrigerators [10], heat pipes [11–13], thermosyphons [14,15] along with many other applications [16,17].

The effective parameters in nanofluid pool boiling heat transfer are nanoparticle material, average diameter, volume/mass fraction, heater's material, surface roughness, type, shape and base fluid. Different nanoparticles, such as Al_2O_3 [18–22], TiO_2 [23–25], SiO_2 [26–28], ZnO [27], ZrO_2 [29], Cu [18,30], CuO [31,32] and nanotubes such as carbon nanotubes (CNT) [33–36], have been widely used. Besides, Newtonian [37] and non-Newtonian [38] types of nanofluids were employed in experimental and numerical pool boiling heat transfer studies. There are also comprehensive reviews on nucleate pool boiling heat transfer and pool boiling critical heat flux using different nanoparticles, which reported both enhancement and deterioration depending on different important parame-

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.01.116
0017-9310/

Nomenclature

A	area (m^2)	V	voltage (V)
h	heat transfer coefficient (W/m^2 K)	X	uncertainty variable
HTC	heat transfer coefficient (W/m^2 K)		
I	amperage (A)	*Subscripts*	
Q	heat loss (W)	c	contact
q''	heat flux (W/m^3)	nf	nanofluid
R	resistance (°C/W m^2)	s	surface
T	temperature (K)	sat	saturation
U	uncertainty	th	thermocouple

ters such as heater size and shape, nanoparticle average diameter and materials [39], as well as nanofluid fraction ratio, roughness of the heated surface, size of cavity and nucleation sites [40].

Recently, Das and Bhaumik [41] have analytically developed a correlation to predict heat flux of pool boiling on a mechanically polished stainless steel plate for two different nanofluids, namely gamma-Al_2O_3 and TiO_2 nanoparticles dispersed in water, by considering temperature, volume fraction and nanoparticle parameters. This correlation was based on thermophysical properties of nanofluids such as heat capacity, density, viscosity and thermal conductivity calculated with well-known correlations. Brownian motion of nanoparticles, cluster/particle agglomeration and development of the liquid layer over the plate surface were neglected in their study, and their correlation was validated against the experimental data existing in the literature.

In another study, Naphon and Thongjing [42] experimentally investigated the effect of nanofluid concentration and pressure on pool boiling heat transfer on a cylindrical heater at different pressures of 50, 100 and 150 kPa. Nanofluids were prepared by dispersing TiO_2 nanoparticles in two different base fluids, R141b refrigerant and ethylene glycol, with volume fractions of between 0.01% and 0.075%. They concluded that both volume fraction and pressure played an important role in pool boiling heat transfer. The increase in volume fraction for nanofluids with both base fluids caused a deterioration in heat transfer compared to the pure base fluid.

In the study of Suriyawong and Wongwises [24], pool boiling heat transfer of TiO_2 nanoparticles dispersed in water was investigated for volume fractions of 0.00005, 0.0001, 0.0005, 0.005 and 0.01%. Copper and aluminum circular heaters with roughness of 0.2 and 4 μm were utilized as heaters. Enhancement in heat transfer was reported to only occur for nanofluids with the volume fraction of 0.0001 vol.% for the copper heater. For aluminum heater, deterioration in heat transfer was observed for all the concentrations. The decrease in roughness also had a positive effect on heat transfer.

The effects of TiO_2 nanoparticles, which had an average diameter of 21 nm and were added to R141b refrigerant with volume concentrations of 0.01, 0.03 and 0.05%, and pressure (in the range of 200–500 kPa) on pool boiling heat transfer on a cylindrical copper heater, were examined by Trisaksri and Wongwises [25]. They found that an increase in volume fraction resulted in degradation in pool boiling heat transfer compared to the pure refrigerant, particularly at higher heat fluxes.

Sarafraz and Hormozi [32] experimentally investigated the effect of surfactants such as sodium dodecyl sulfate, SDS, sodium dodecylbenzene sulfonate, SDBS and Triton X-100 in CuO nanoparticles/water nanofluids on nucleate pool boiling heat transfer. Their results reported deterioration in pool boiling heat transfer in the absence of surfactants, whereas the addition of surfactants led to heat transfer enhancements. The mass fraction of copper oxide nanoparticles was in the range of 0.1% and 0.4%. The highest enhancement was obtained for the highest mass fraction ratio (i.e. 0.4%) and SDS as a surfactant (up to nearly 70%). The authors also have some other studies on different nanoparticles such as Al_2O_3 dispersed in ethylene glycol [20] or in water [43], carbon nanotube (CNT)/water nanofluids [36] and nanofluids with ZrO_2 nanoparticles in a mixture of water and ethylene glycol [29].

Hegde et al. [31] conducted experiments on pool boiling critical heat flux (CHF) of nanofluids with CuO nanoparticles at volume fractions from 0.01% to 0.5%. For all the concentrations, critical heat flux enhancements were above 60%, and the highest enhancement (about 130%) was pertinent to the optimum volume fraction of 0.2%.

Despite the fact that a large number of studies have focused on pool boiling heat transfer of nanofluids, there still exists a strong motivation to focus on this subject, particularly on nanofluids with CuO nanoparticles, on which only few investigations can be found, and on the effect of nanoparticle stability on pool boiling. In this regard, pool boiling heat transfer of TiO_2 nanoparticles/water and CuO nanoparticles/water nanofluids was experimentally explored at different volume fractions over an aluminum flat plate heater. Visualization was carried out as well to observe the boiling images and to link it to the heat transfer performance. For CuO nanoparticles/water nanofluids, where the stability of nanoparticles was rather less, the surfaces were tested after the nanofluid experiments with the pure base fluid to shed light on heat transfer enhancement with CuO nanoparticles. As a result, the results were bolstered with both boiling images and repeated tests with the pure base fluid.

2. Experimental setup and procedure

The pool boiling experimental setup is schematically displayed in Fig. 1. It has a glass pool of 6 mm thickness having dimensions of $50 \times 50 \times 50\ mm^3$, which was sandwiched with an aluminum plate heater with dimensions of $62 \times 62 \times 25\ mm^3$ through two holder plates. The heater has four holes at the bottom part of the heater (2 cm below its surface), where the cartridge heaters (Istanbul Resistance Co., Turkey) were press-fit and high quality conductive grease was used for filling the air gap around the heater. The gasket sealing elements were used between the glass pool and the holder plates to prevent leakage and heat dissipation. The heater plate has also three small holes for inserting K-type thermocouples (Omega Engineering Inc., USA) in order to measure the surface temperature at the close proximity of the heater surface (0.8 mm below the surface), which is in contact with the working fluid. A T-type thermocouple (Omega Engineering Inc., USA) was also inserted to the fluid to measure the saturation temperature of the nanofluids. A reflux condenser (ISOLAB GmbH, Germany), with inner and outer glass tubes diameters of 22 and 40 mm,