Analysis of Experimental Studies on Pool Boiling Characteristics of Nanofluids

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Abstract— Presently, pool boiling critical heat flux (CHFs) and heat transfer coefficient (HTC) are observed in nanofluids using alumina (Al2O3) and multiwall carbon nanotubes (MWCNTs) nanoparticles dispersed distilled water. For the purpose, pool boiling characteristics of distilled water are first observed and validated using Rohsenow's correlation. Nanofluids are used at nanoparticle weight of concentrations of 0.01%, 0.03% and 0.1%. In order to enhance the dispersion stability surfactants sodium dodecyl sulphate (SDS) and Triton X-100 are used with 1% concentration, individually. The experiment is carried out using a electrically heated stainless steel wires for studying CHFs and stainless steel cartridge heatersfor studying HTCs. The comparison of boiling CHFs is done from bare and nanoparticles deposited surfaces in distilled water. Also, the effect of adding the surfactants in the nanofluids is measured on the mentioned parameters. It is noticed that pool boiling characteristics get affected by nanoparticle concentration with added surfactants. HTC deterioration is measured with enhanced nanoparticle concentration while CHF increment is noticed with decreasing nanoparticle concentration. In all, CHFs increment upto 150% is observed, while up to 50% deterioration in HTCs is observed at heat flux is within a limit of 100kW/m2 to 500kW/m2.

Key words: Pool Boiling; Nanofluids; Surfactants; Particle Deposition; Critical Heat Fluxes (CHFs); Heat Transfer Coefficient (HTC)

Highlights:

- Alumina and MWCNTs nanofluids are used for pool boiling studies.
- CHF increment upto 150% and HTC deterioration of about 20% is observed.
- Relative increment in HTC is observed when using surfactants.
- Particles deposited on a heater surface is reasoned for change in pool boiling characteristics

I. Introduction

Nanofluides are colloidal suspension of nano-sized particles (10-9m) in the based fluids. Ever since the term was framed by Choi in 1995 at Argonne National Laboratory for this field of nanotechnology, numerous experiments had performed to put front the remarkable heat properties of this particle fluid suspension. At mere concentrations ranging within 10-3% to 5%, these engineered fluids have displayed increased thermophysical properties like thermal conductivity, HTC and CHF.Various possible reasons are put front for these enhanced properties, like, high surface area to volume ratio, Brownian motion, thermophoresis, cohesion and high conductivity of nanoparticles. Some commonly studied nanoparticles are metals (e.g. Cu, Au, Ag), oxides (Al2O3, SiO2, CuO), and carbon nanotubes. The base fluides used for suspension are water, ethylene glycol (EG) and refrigerants. These particles provide uniform dispersion under optimum range and give stable suspension of particles for long time.

II. Analysis Of Nanofluids Pool Boiling

The studies in case of pool boiling [1] and hydrodynamic theory of burnout crisis [2] are being done since decades as the result display maximum of heat flux limit due to burnout conditions. When the heat fluxes reach t\he critical point, the surfaces which are being heated, are covered by using rapidly formed of vapour bubbles, thereby reducing the direct contact between fluid and a heater surface. This causes the temperature of a heating surface to increase drastically resulting in burnout the material. Thus an efficient heat management systems allowing higher critical heat flux must be developed. Choi et al. [3] \performed experiments with metal and metal oxide nanofluids and displayed enhanced thermal conductivity. Taking inspiration from this study several experiments had performed for the study pool boiling characteristics of nanofluids.Similarly, the experiment done by Jung et al. [4] showed 200% increment of CHF using alumina-water nanoparticles, whereas Tu et al. [5] obtained 60% increment in HTC. Bang and Chang [6] performed experiments under sub-atmospheric conditions and found increment in CHF. Kathiravan et al. [7] used surfactants with Cu- water nanofluids and found deteriorated CHF compared DI water.

The above mentioned characteristics also highly depend on the method of preperation of the nanofluids. It involves two techniques: top down approach through size reduction, called method of two steps , bottom to up through simultaneous dispersion and production of nanoparticles, known as one-step method. There are number of top-down (optical lithography, E-beam lithography, soft and tiny imprint lithography, scanning probe lithography, etc.) and bottom-up approaches (atomic layer deposition, sol-gel nanofabrication, molecular self -assembly, chemical and physical vapour phase deposition, DNA-scaffolding etc.) presrntly used for the preparation of the nanofluids. Every apporach has its own advantages and disadvantages. However to prepare the nanofluids largrly depends to the property of the used base fluid, sizeof particles, concentrations of nanofluid, and dispersants (surfactants). Further, the stability is dependent on the properties like thermal conductivity, surface tension,pH value,viscosity etc.

III. Literature review

Since the day term "Nanofluids" was coined by Choi in 1995 at Argonne National Laboratory, several experiments had performed with this new substance, courtesy of the scouting and inquisitive nature of scientists and scholar through out the world. Exploring application of nanofluids in all aspects of life and sciences such as electronics, cooling systems, automobile industry, power plants, defence and biomedical applications, nanofluids have already shown remarkable characteristics via their enhanced thermos-physical characteristics and there nature of modifying the morphology of surfaces around. Pool boiling has attained special attention with the progressing study in the field. Till date approximately 350 journals have been published on the permutations and combinations of different nanomaterials and base fluids along different concentration space, giving detail study of various characteristic parameters affecting the pool boiling. Fig. 1 obtained from Web of Science gives yearly comparison of journals studying the pool boiling characteristics of nanofluids.

A. Pool boiling characteristics of Alumina based nanofluids

When nanofluids were invented by Choi and his group at the Argonne National Laboratory, they first tried to use oxide particles of nanometer size to suspend in the common coolants (e.g. water, ethylene glycol). Oxides were used because they are easy to manufacture and stable compared with pure metal particles, which can not be suspended without using an agglomeration. Subsequently, many investigators carried out experiments with oxide particles, predominantly Al2O3.The following section, we discuss the outcome of experiments and their general trends.

The studies authors did on Al2O3 nanofluids covers aspects of different heater types used, nanoparticle sizes, concentration and usage of stabilisers.As the presence of nanoparticles and such other variables, the results differ vastly. While Das et al. [71], Bang and Chang [6], Kim et al. [73], Jung et al. [4], Shahmoradi et al. [74] discuss the deterioration of the HTC by up to 40%, Taylor and Phelan [72] shows inhancement of the HTC of exact same measure.Beside this everyone of them agree for the increment of CHF, max to 200%. On the boiling curve particle surface deposition and the affect of difference between nanoparticle surface roughness and size are also discussed.

You et al. [11] studied boiling transfer of heat with Cu plate in sub-atmospheric pressures and reported enhancement of CHF. Tu et al. [15] reported increment of about 64% in CHF and HTC with 38nm size particle on Ti-Plate. Wen and Ding [13] observed that the heat transfer of pool boiling on disc and reported 40% HTC enhancement, with increment in HTC with increasing concentration. Also since the deposition of particle was not observed the outcomes were deemed to be inconsistent with the previous studies. Kim et al. [14, 15] observed enhancement of CHF and credited a change of surface morphology for the particle deposition was same. Also the existance of porous layer causes to a decrease in the angle of contact and HTC because of thermal resistance. Coursey and Kim [17] examined CHF on block surfaces of copper and found them in correlation with concentration of nanoparticles and surface wettability with 37% increment of CHF. Soltani et al. [20] used SS cartridge heater of 76mm diameter and 2mm thickness with Al2O3 nanofluids and showed 30% enhancement of HTC. Golubovic et al. [21] evaluated the affect of particle characteristic under the pool boiling and observed that the CHF increased max to 50% for alumina nanoparticles. Also the angleof contact decreased to 33° on the surface from 90°of pure surface and thus was quoted the main cause of the enhancement of CHF.

B. Kim and Kim [23] used Ni-Cr wire of 0.2mm ,

found enhancement of CHF to 170%,reported the causes for this as enhanced surface wettability,capillary wicking and surface roughness performance. Kwark et al. [27] studied the behavior of low concentration over copper plate and reported deterioration of HTC with 80% increament of HTC at 0.0007 vol%. Truong et al. [29] used sandblasted SS surface and reported 35% increment of CHF compared to base fluid. Phan et al. [30] used SS heater foil and observed significant decrease in HTC, about 50%. They also said that the thickness of nanoparticle layer depends upon the concentration of particles and the duration of the test. Wen et al. [34] and Wen [39] carried out studies on smooth and rough brass surfaces in nucleate regime. They reported that deterioration and enhancement in HTC depending upon the particle size and surface roughness. Harish et al [35] used electro-stabilized nanofluides with rough and smooth heaters. Reported that the different particle surface interactions can be brought to either plugging of surface cavities or splitting, thus deteriorating or enhancing heat transfer of boiling. Pham et al [38] used inclination of SS plate as surface of test and reported enhancement of CHF with increase in inclination angle.

Ahmed and Hamed [43] investigated that during the pool boiling transient nature of deposition with enhancement at 0.01vol% and deterioration thereafter. This enhancement was reasoned by the increased thermal conductivity. Raveshi et al. [48] studied pool boiling of nucleate with water and EG as base fluids and noted 64% increment of HTC at 0.75vol%. Ahn and Kim [49] reported 136% increment of CHF with plain copper heater. Increase of surface wettability and there is a decrement in no. of nucleation sites which were active, was observed. Lee et al. [53] showed that CHF increment of nanofluids as the increasing system pressure, results in the higher frequency of bubble and contact angles are lower. Xu and Zhao [55] noted that nanofluids concentration, material size and copper foam structure affected pool boiling performance considerably.

C. Pool boiling characteristics of Carbon Nanotubes (CNTs) based nanofluids

The next breakthrough in the innovation of nanofluids, which also came from the group at Argonne National Laboratory, was with carbon nanotubes. The nanotubes were straight and they were dispersed in synthetic efin oil. They got stable suspension with 1 vol% nanotube loading. The thermal conductivity was found to be around 2500 W/m-K on an average. These results took nanofluids researchers by storm. It was found that with as small as a 1 vol% fraction, over 159% enhancement in thermal conductivity of base fluid can be obtained. Thus is the following section we will discuss the results of experiments of pool boiling characteristics of CNT based nanofluids. The studies by Amiri et al. [7] with CNT-water and CNT-Ag-water nanofluids with plate type heater and CNT dimensions 60nm x 15 nm shows enhancement in HTC with increasing concentrations ranging from 0.01-0.1 wt.%. It is observed that with the increasing diameter of CNTs the HTC decreased. Also, enhancement for covalent nanofluids and deterioration for non-covalent nanofluids was described. Hashemi et al. [21] used smooth flat plate copper heater with polyvinyl pyrrolidone polymer (PVP) stabilised CNT-water nanofluids. The HTC was found to be lower than that of pure water. However, even at just 0.001 vol% concentration, 200% increase in CHF was exhibited. Also, CNT deposition was observed with resulted in reduced active nucleation site, bubble generation and thus decreased HTC. Liu et al. [25] observed 130% enhancement in HTC and 200% enhancement in CHF at pressures of 7.4 kPa and 0.5-4 wt. % concentration. The enhancement was credited to the surrounding low pressure as; with 100 kPa pressure only 60% enhancement in HTC and CHF was observed. Shoghl et al. [54] reported enhancement in both HTC and CHF with the used of SS (stainless steel) cylindrical heater (Ø 10.67 x 99.1mm^2). Sarafraz et al. [70] performed experimental investigations of functionalized and non-functionalized CNTs with DIW and reported highly stable nanofluids with stability of up to 3 weeks. Strong increment in CHF and deterioration of HTC was observed due to fouling of test surface resulting in lower liquid droplet contact angle and increased wettability.

D. Pool boiling characteristics of Other Nanoparticles based nanofluids

Several other nano-materials like oxides, carbides, diamond and pure metals are also tested for the detailed studies of nanofluids to generate an empirical relation giving generalised characteristics in thorough study. Some studies are discussed in the following section.

Yang and Maa [8] studied Au with SiO2 nanofluids with EG and H2O under ambient condition with Cu plate as heater surface. They reported 21% HTC enhancement for Au, while it deteriorated for SiO2. Also HTC improved with increase in concentration. Vassallo et al. [11] performed experiments with SiO2-water nanofluids using Ni-Cr wire heater surface under atmospheric conditions and noted 200% increment in CHF. Liu et al. [15] investigated CuO-water nanofluids of different concentration and pressure. They reported significant increment of HTC and CHF with decreasing pressure. Also HTC and CHF increased slowly with conc. achieving peak at optimum value of 1.0 wt.% beyond which HTC decreased because of excessive change in the morphology of the surface.

Huang et al. [33] experimented with TiO2-water nanofluids at 0.01 from 1 wt.% and reported 82.7% in CHF with decreased HTC. The altered morphology of the surface is because of the coating of nanoparticles and not because of dispersed nanoparticles into the base fluid caused enhancement of CHF and increases the wettability of the surface, and the deterioration of HTC genertes higher thermal resistance. Heris [36] investigated CuO-EG-water nanofluids with heater cartridge, reported enough increment in HTC as observed increase in active nucleation site. Yang and Liu [37] conducted experiments with functionalised and traditional SiO2-water on Cu bar under ambient and sub-atmospheric conditions. They observed that as traditional nanofluids causes deterioration in HTC and increment in CHF, functionalised nanofluids showed slight enhancement in HTC as compared to that of water, but CHF stands still. Sheikhbahai et al. [40] studied boiling heat transfer of Fe3O4-EG-water nanofluids with thin Ni-Cr wire heater. He reported that decrement in HTC but CHF increased by 100% because of surface modifications. Okawa et al. [41] performed transient HTC study with TiO2-water nanofluids. Here HTC first decreased, and thereafter increases before reaching equilibrium. They reported 91% enhancement in CHF as an increase in time of the boiling. H. Sakashita [42] also observed 1.8 times increased value of CHF compared to the bare surface for TiO2 coated surface.

Lee et al. [44] observed the affects of, titania, alumina and magnetite nanofluids. CHF was increased as the increase of particle concentrations with max value for magnetite. Kole and Dey [45, 46] studied ZnO-EG nanofluids but reported CHF enhancement ranging from 22% to 117% for conc. from 0.016vol% to 2.6 vol% respectively. Vazquez and Kumar [50] investigated enhancement in CHF and BHF (burnout heat flux) with silica nanofluids using Ni-Cr ribbons and wires embedded in the pyrex glass of cylindrical test pool. They reported CHF increment and reasoned change in surface's hydrophilicity for the same. Song et al. [56] observed the CHF value of SiC nanofluids on two different SS plates in polycarbonate pool under ambient pressure. The wettability and thick deposited surface change were main reason for CHF increment. Kim et al. [57] used a thin Ni-Cr wire, which was electrically heated and observed the effect of the properties of surface of the deposited layer. They observed that the thickness of the nanoparticle layer and capillarity shows correlations with CHF values,compared to wettability. Naphon and Thongjing [61] used TiO2-R141b nano-refrigerant with a cylindrical heater made up of brass and reported deteriorated HTC. In addition HTC increases under high boiling pressures an decreasing the size of bubble.

Mori et al. [63] experiments on a plain by installing honeycomb porous plate, nanoparticle deposite surface and reported increased CHF and decreased HTC withTiO2-water nanofluids. Umesh and Raja [65] performed experiments with CuO-Pentane nanofluids on enhanced and smooth circular brass surface. Here HTC enhanced by 15%-25% lower concentration of 0.005 vol%, and observed the enhancement with increasing concentrations; also the enhancement was higher at lower heat fluxes than at higher heat fluxes. Kamatchi et al. [68] used nanofluids as rGO-water with thin Ni-Cr wires,which are electrically heated. Remarkable increment in CHF within a range of 145% to 245% was observed. It was identified that rGO made a porous layer on the wire surface and the thickness of the formed layer is increased with the concentrations. Sarafraz et al. [69] experimented with ZrO2-WEG50 nanofluids at concentrations of 0.025-0.1vol%. Here, slight deposition was observed with no impact on the HTC, but CHF increased by 29%. They observed a formation of porous layer,results in increased capillary wicking action and increased CHF with decreased contact angle.

IV. RESEARCH GAP & OBJECTIVE

From the literature review it is observed that numerous nano-particles and solution combinations have been used for observing the pool boiling behaviour of respective nanofluids. In the present study solution of water based

Alumina and MWCNT nanofluids are used. The particles are used at weight concentration of 0.01%, 0.05%, 0.1%. The results obtained are then compared with those of surfactant solution based nanofluids. Here, 1% concentration of Triton X-100 and SDS (Sodium Dodecyl Sulphate) are individually mixed in water. The nanoparticles are then ultrasonically dispersed to create suitable nanofluid.

Visual microscopic study of surface fouling andeffect of bubble formation is studied during boiling to analyse the variation in CHFs and HTCs. The studies are then done as follows:

- Dispersion stabilising of nanoparticles in nanofluids with and without surfactants at given concentration.
- Variations in boiling heat transfer for nanofluids.
- Variations in critical heat flux for nanofluids.
- Comparison with effect of surfactants on boiling parameters
- Effect of particle deposition on boiling parameters.
- Comparative analysis of boiling parameters under different solutions

V. Conclusion & Discussion

Presently, pool boiling HTCs and CHFs are measured via SS wire heater and cartridge heater surfaces immersed in liquid at near saturation temperature. MWCNT and alumina nanofluids are used with particles dispersed weight concentrations of 0.01%, 0.05%, 0.1%. To confirm dispersion and to observe effect of surfactants, SDS and Triton X-100 dispersants are used. From the set of experiments performed, following conclusions can be drawn:

[1] Nanofluids enhance the critical heat flux for the pool boiling case irrespective of the used particle and the dispersion practice employed. Even at lower concentrations of 0.01%, MWCNT-Water based nanofluids provided a maximum enhancement of 155%. CHF enhancement is also observed to be increasing with decrease in nanoparticle concentration. It is noted that surfactant based nanofluids give lower CHF enhancement while compared with pure water based nanofluids. Overall the critical hat flux enhancement lies within the range of 50% - 150%.

[2] In this case HTC deterioration is seen for all the range of nanofluids when compared with the pure water. HTC deterioration is seen within the range of 20%-50%. Although when surfactants are used, a slight increment in heat transfer coefficient is noted because of surface wettability enhancement by deposition of particle and physical change in properties of liquid.

[3] The deposition of particle images show deposition with different concentrations for different nanoparticles. The deposition is found to be stable even in the presence of new liquid environment, suggesting the presence of an adhesive force binding the particle to the surface. Change of surface morphology also verifies with the active nucleation site, enhanced heat transfer and surface wettability, thus decreasing the heat transfer coefficient and enhancing critical heat flux.

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