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Experimental study on pool boiling and Critical Heat Flux enhancement of metal oxides based nanofluid

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ABSTRACT

Critical Heat Flux or CHF is a phenomenon in pool boiling, which limits the thermal flux during the nucleate heating phase. Presented research paper is an investigation of the CHF of Al_2O_3, Fe_2O_3 and CuO nanoparticles in water as base fluids. Critical Heat Flux of water and nanofluids were measured at 100 °C and 0.10325 MPa using 29 × 22 W DC power supply and NiCr 32AWG wire as the primary heater. Concentration of nanoparticles in the respective base fluids was varied from 0.01 vol% to 0.1 vol% in the step of 0.1%. Nanofluids were used as the working fluid and sent to circular bath. A significant enhancement in CHF was found of nanofluid over base fluid is found in the study. As the concentration of nanoparticles in water increases, the CHF also increases up to their optimum concentration and then starts to drop and almost becomes constant at 0.1%. The enhancement is due to enhanced surface wettability, increased heat transfer coefficient and nanoparticle deposition on heating element. The decrease in CHF over higher concentration is due to probable agglomeration due to prevalent surface charges of nanoparticles.

1. Introduction

Critical Heat Flux (CHF) is an observable fact resultant to the point where a liquid contact cannot be maintained at the heated surface. Many significant industrial applications rely on nucleate boiling, to remove high-heat flux from a heated surface which includes cooling of chemical reactor, nuclear reactor, electronics system. In most of the applications, it is important to keep the heat flux of fluids below the critical value of heat flux. Obviously, we require a high-heat flux fluid so that, it can be use in a cooling system based on nuclear boiling [1]. Nanofluid is the suspension of nanoparticles in a conventional base fluid like water, EG, etc. [2]. One of the remarkable characteristics of nanofluids is that it possessed superior properties to its conventional counterparts. The enhanced thermal conductivity, heat transferred coefficient; enhanced surface wettability and Critical Heat Flux (CHF) are some of the salient features of nanofluids [3].

Nanofluid is a potential working fluid, which is used in various high-heat flux systems to remove the undesired heat. Nanofluid is a suspension of nanoparticles within the fluid which has at least one dimension should be in the nano range. Various researchers studied the thermo-physical properties of nanofluid e.g. thermal conductivity, specific heat capacity, surface tension, density and viscosity. Addition of nanoparticles in the conventional fluids like water, ethylene glycol increases the CHF in a very effective way. Various metallic oxide nanoparticles were used for the preparation of nanofluids e.g. CuO, TiO_2, Al_2O_3, Fe_2O_3, carbon nanotubes etc. [4–7].

Song et al. synthesized the Silicon carbide (SiC) based nanofluid to find out the thermal performance in water pool boiling CHF experiment. The study showed that the 105% enhancement in CHF value for very low concentration (0.01%) of nanoparticles. The stainless steel material were used for the heater; all tests were done under atmospheric pressure, saturated condition [8]. In boiling heat transfer the maximum peak obtained, which is the Critical Heat Flux point below that point a boiling surface continue to stay in the nucleate boiling regime and beyond this point, there is a transition from nucleate boiling regime to film boiling regime.

Critical Heat Flux or CHF is a phenomenon in pool boiling, which limits the thermal flux during the nucleate heating phase. [9] It is attributed to the formation of vapor blanket around the heating surface which results in localized heating and meltdown of heating surface. In pool boiling, the heater is completely immersed in the stagnant fluid. In case of nucleate boiling, the temperature of heating surface is slightly greater than that of saturated fluid temperature. As the temperature of heating surface increases, the flux of heat to the fluid also increases due to Newton's law of cooling. At CHF, the stagnant fluid surrounding the heating surface starts to change the phase due to excessive surface

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Nomenclature

∅ = volume fraction
δ_f = Density of fluid, kg/m^3
δ_p = Density of particle, kg/m^3
T_o = Reference temperature in °C
T_w = Temperature of heating material in °C
A = Area, m^2
q_{CHF}: Critical Heat Flux (W/m^2)
VI: Power supplied (W)
d: Diameter of the test wire
L: length of the test wire
R_T, R_o = Resistances at respective temperatures in ohm

temperature. It causes the localized heating of the fluid molecules surrounding the surface. Due to the phase change, the fluid gets converted to vapor and forming the uniform vapor blanket around the heater. As the thermal conductivity of vapor is considerably lower than the fluid, this causes the heat-transfer coefficient h to decrease drastically decrease and thus the heat flux starts to decrease beyond the CHF point. CHF is the maximum heat flux that can be drawn by the fluid under given conditions of temperature and pressure.

Aforementioned, CHF of nanofluids is superior to its conventional counterparts. The first paper to mention is by Yu et al. [10] in 2003. They have reported on the CHF of Al_2O_3-water nanofluids in a pool boiling experiment using polished copper surface as a heater. They found over 200% increment in CHF of nanofluid over water at 0.05 g/l of Alumina nanoparticles. Since then many researchers [10,12–15] have worked on the similar nanoparticles like TiO_2, SiO_2, ZnO, etc. and reported appreciable enhancement in CHF. The main reason for CHF enhancement in nanofluids is attributed to the surface wettability due to nanoparticle incorporation. Kim et al. [16] in 2007 have reported a significant reduction in contact angle between nanofluid and heater surface leading to the increase surface wettability and preventing coolant run out from the heater. Some researchers have carried out the CHF experiment using the coating of nanoparticles directly on the heater surface. Stutz et al. [17] in 2011 carried out the experiment with γ-Fe_2O_3 nanoparticles on Platinum heater using rigorous boiling and electroplating. They have reported the remarkable increase in heat transfer coefficient and CHF. There is an irregular increase in CHF of various nanofluids with concentration [18] (Kim et al.). At lower nanoparticle concentrations, the CHF increases considerably but as the concentration further increased it starts to drop. This is due to agglomeration of nanoparticles at higher concentration [19]. Park et al. [20] in 2009 have carried out the nucleate boiling experiment with MWCNT and water and observed enhancement in CHF is over 200%. They carried out research for heat transfer coefficient enhancement also. The method of functionalization used is physical treatment with PVP (polyvinyl pyrrolidone) as a surfactant. Sakashita et al. [21] in 2015 has reported the pressure dependence of CHF TiO_2 nanofluid. During small range pressure 0.1–0.8 MPa there is appreciable increase and then decrease in CHF but as further the pressure is increased the gradient stops means there is no change in CHF at the higher pressure. This is because at the lower pressure, there is significant enhancing in surface wettability and then no longer plays the role at the higher pressure.

As stated earlier, CHF is the maximum heat flux that can be drawn from a heating surface, and it is a property of the fluid. If beyond the CHF, heating is continued, the vapor no longer to transfer heat from the surface causes the heating of heating surface itself. Due to this localized heating, the enhanced temperature of heater element causes its meltdown, which is not at all palatable. In nuclear reactors, when the heating surface experiences the draught of coolant due to CHF, the meltdown of reactor causes serious problems like spread of radiations to the surrounding environment which has various side effects on environment.

Nanoparticles have proven to be useful in enhancing CHF of base fluids. Nanofluids show remarkably high CHF, which is why they are proven to be excellent coolants in the operations demanding high thermal flux. Various researchers have explored this field and reported the enhanced CHF in nanofluid boiling of various nanofluids like Al_2O_3, SiO_2, CuO, etc. Given research work is focused on fabrication of CHF measurement instrument, its calibration, evaluation of CHF of Al_2O_3, CuO, Fe_2O_3 nanoparticles in water.

2. Experimental work

2.1. Nanofluid preparation and stabilization

The nanofluid for the present study was prepared by the two-step method. Two-step method is the most widely used methods for preparing nanofluids because it is the most economic process to synthesis nanofluids. The nanoparticles used for the experimental purpose are Al_2O_3, CuO and Fe_2O_3. The addition of nanoparticles in the base fluid causes agglomeration or poor suspension of nanoparticles. To overcome this problem, ultra-sonication agitations were used for proper dispersion of nanoparicles in the base fluid. Kim et al. [22] were prepared alumina (Al_2O_3), zirconia (ZrO) and silica (SiO_2) water based nanofluid. The concentration of the nanofluid was taken 10% by weight and nanofluids were then diluted with deionized water to the low concentrations of interest for the CHF experiments, i.e., 0.001%, 0.01% and 0.1% by volume. Azmia et al. [23] prepared the titanium oxide (TiO_2) and aluminium oxide (Al_2O_3) based nanofluids in water ethylene glycol (EG) by the two-step method. Ultrasonication was used for the proper dispersion of nanoparticles for 2 h. Wang et al. [24] synthesize the Al_2O_3 based nanofluid in deionized water by the two-step method. The method in which the first, nanoparticles were injected in deionized water and for better stability and dispersion of nanoparticles ultrasonic vibration units used.

For the preparation of nanofluids for this work, aluminium oxide nanoparticles were dispersed in deionized water for different concentration of nanoparticles (0.01, 0.02, 0.03, 0.05, 0.07 and 0.1%V.) was taken. The mixing is done by ultra-sonication treatment. The sonicator probe was dispersed in nanofluid and ultra-sonication waves were passed through it. The sonicator has 1720 W of maximum power, and power was adjusted accordingly. The sonication was carried out for 1–2 h. After sonication the nanofluid was allowed to cool at an ambient temperature to remove excess heat due to sonication. For the stability checkup, the nanofluid was kept in closed beakers for several weeks. This ensures possible overestimation of stability and elimination of experimental errors. In similar fashion nanofluids of CuO and Fe_2O_3 was engineered and stabilized.

The density of nanofluids was calculated using the correlate:

$$\delta_n = \delta_p \varnothing + \delta_f (1 - \varnothing) \quad (1)$$

where,δ_n: *d*, δ_p: density of particles, δ_f: density of fluid.∅: volume fraction of nanoparticles.

Low concentration of nanoparticles addition ensures the low heat of vaporization. All the experiments were essentially carried out at pH of 7.

2.2. Experimental setup

Experimental setup for measuring the Critical Heat Flux (CHF) has shown in Fig. 1 through various literature surveys, the design was proposed, which consists of a glass bowl of 5 l supported on a steel