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Investigations on Heat Transfer Enhancement in Pool Boiling with Water-CuO Nano-Fluids

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The main focus of the present work is to investigate Critical Heat Flux (CHF) enhancement using CuO nanofluid relative to CHF of pure water. To estimate the effect of nanoparticles on the CHF, pool boiling CHF values were measured for various volume concentrations of CuO nanofluid and compared with pure water. CHF enhancement of 130% was recorded at 0.2 % by volume of CuO nano-fluids. Surface roughness of the heater surface exposed to three measured heating cycles indicated surface modifications at different volume concentrations of nanofluid. SEM image of the heater surface revealed porous layer build up, which is thought to be the reason for CHF enhancement.

Keywords: Nanofluid, pool boiling, CHF, enhancement, nano-particle**.**

Introduction

Many industrial systems like boilers, thermal-hydraulic systems, condensers etc. utilize phase change of the working fluid to get the desired end results. Comparatively less research work has been reported about phase change of a fluid or boiling phenomenon and in particular heat transfer considering the economical efficiency of the systems. The boiling transfer phenomenon may occur in the following forms, namely: pool boiling, forced convection boiling, sub-cooled boiling, and saturated boiling. Unique features of boiling and condensation are, heat transfer to and from the liquid can occur without influencing the fluid temperature; the rates of heat transfer and heat transfer coefficient are much higher due to latent heat associated with phase change than the normal convection process and high rate of heat transfer is achieved with small temperature difference. Pool boiling CHF is the point where nucleate boiling goes through a flow regime transition to film boiling with a continuous vapor film separating the heater and the liquid. CHF is the condition where the vapor generated by nucleate boiling becomes so large that it prevents the liquid from reaching and rewetting the surface.

The boiling phenomenon with the limitation condition CHF that causes an abrupt temperature rise and the physical destruction of the heated surface according to the sudden transition from efficient wall-liquid zone with nucleate boiling to wall-vapour zone with film boiling, can be further regarded as the key area of interest for the upcoming researchers.

In this context it is better to understand CHF characteristics considering the safety of various high-heat flux thermal-hydraulic systems.

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Over the last decade, lots of effort have been put in for experimental and theoretical studies concerning CHF under forced convection boiling conditions yielding a lot of models or methods for prediction of the CHF and its characteristics for various applications [1]. During this period many aspects of CHF have been understood to some extent, experimental investigations are usually limited to the simplified geometry due to the high expenditure and complexity. With no single or universal CHF correlation available usable for various geometries and contradictory claims by researchers, CHF continues to be studied. In addition to this, the research activities for the CHF are focused on CHF enhancement techniques to increase the economic efficiency and safety margins of the energy systems. Recently, 'nano-fluids', a new kind of heat transfer fluid in which nano-particles are uniformly and stably dispersed, has been considered for the enhancement of pool boiling CHF. The main focus of the present work is to investigate CHF enhancement using CuO nano-fluids relative to CHF of pure water.

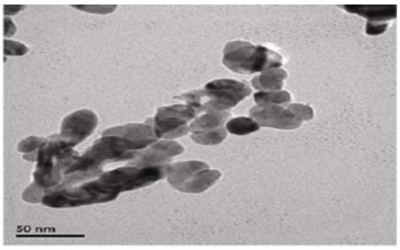
Pool Boiling Experiment

The poll boiling experiment can be subdivided into preparation and characterization of nanofluids and CHF experiments with NiCr wire as explained follows.

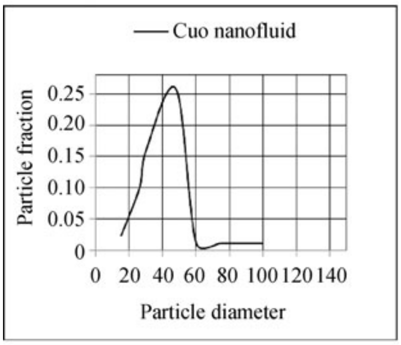
Preparation and characterization of nanofluids

In this work, nanofluid was prepared by the two-step method, dispersing dry nanoparticles into the base liquid. Distilled water was used as the base liquid, and CuO nanoparticles were used without the addition of additives. The CuO nanoparticles were procured from Nano Amor Technologies Corporation having 99% purity with an average size of 50nm. It can be noted that additives (dispersants or surfactants) could have been used to stabilize the nanoparticle suspensions, but the additives could exert a significant influence on the rheological behavior of the fluids and the boiling heat transfer (Wen and Ding, 2005) [2]. Obviously, the present work doesn't use any additives and ultrasonic excitation was performed for 3 h just before pool boiling experiments. It is already reported that nanoparticles dispersed without other additives do not change the surface tension of the base fluid (Das et al., 2003) [3].

The characteristics of nanofluids are governed not only by the kind and size of the nanoparticles but also their dispersion status in the base fluid. Fig. 1 shows nanoparticles dispersed in distilled water. The CuO nanoparticles were spheres with a mean diameter of 50 nm and a range from 10 to 100 nm, as estimated from TEM images. Due care was taken to ensure complete dispersion, as the nanoparticles dispersed with no additive might have the weak electrostatic repulsion between themselves and be easily agglomerated in the colloidal state.



(a) TEM photograph of CuO nano-particles



(b) Size distribution of the nano-particles

Fig. 1 Characteristics of nano-fluid

Since volume fraction of the solution is considered to be the more important factor as compared to mass fraction and as it is very difficult to measure the precise true volume of nano-particles, the following conversion equations are used conventionally. The volume fraction of the fluid is given by,

$$\varphi_v = \frac{1}{\left(\frac{1-\varphi_m}{\varphi_m}\right)\frac{\rho_p}{\rho_f}+1} \tag{1}$$

where φ_m is the mass concentration of nanoparticles, ρ_f is the liquid density, and ρ_p is the nanoparticle density. Five different volume concentrations were prepared ranging from 0.01% to 0.5%. Owing to lower concentrations of the test fluid used in the present work, no considerable enhancement in thermal conductivity (Murshed et al., 2005) [4], viscosity and density can be expected (Brinkman, 1951) [5]. Therefore, the change of the properties of water should have a negligible effect on the present heat transfer results.

From the above equation we can determine the density expression for a solution of liquid–solid as follows.

$$\rho = \rho_f\left(1-\varphi_v\right)+\rho_p\varphi_v \tag{2}$$

The heat capacity of the fluid can be determined using the following relation.

$$\rho C_p = \rho_f C_{pf}\left(1-\varphi_v\right)+\rho C_{pp}\varphi_v \tag{3}$$

CHF experiments with NiCr wire

The CHF of de-ionized (pure) water and CuO nanofluids was measured with a NiCr wire heater of 0.19 mm diameter, horizontally submerged in the test fluid at atmospheric pressure. The main test pool consists of a 250 mm diameter, 150 mm high Pyrex glass vessel and a 30 mm thick Bakelite cover. The simple geometry and glass material of the test chamber ensured clean conditions that could be maintained for each experiment.

The working fluid was pre-heated using a 1kW heating coil wound around a metallic strip of tungsten material. The pool temperature is measured with a RTD thermocouple of K-type. Provision is made at the top of the Bakelite cover plate (10 mm diameter hole) to insert the thermocouple lead wire into the boiling liquid. The cover plate can be secured firmly on the glass vessel containing nanofluid. The hole on the cover ensures atmospheric conditions inside the vessel. The loss due to evaporation and liquid leakage from the plate was estimated to be 1.33%. This loss was compensated by adding the makeup fluid before the next run. Due to this, the volume concentration of the working fluid did not change during pool boiling. A horizontally suspended smooth NiCr wire (test wire) of 0.19 mm diameter was used as a boiling surface. Both ends of the NiCr wire heater were tightly secured to the clamps of the tungsten electrodes. The heat input to the test wire was measured by a digital Watt meter incorporated with "critical heat input sensor". The DC power supply (60V/20 A) was used for this purpose. After being filled into the vessel, all fluids were preheated to saturated temperature using a 1 kW pre-heater. All pool boiling experiments were conducted after the bulk temperature of the working fluid was stabilized at the saturated temperature (100 ^{0}C).

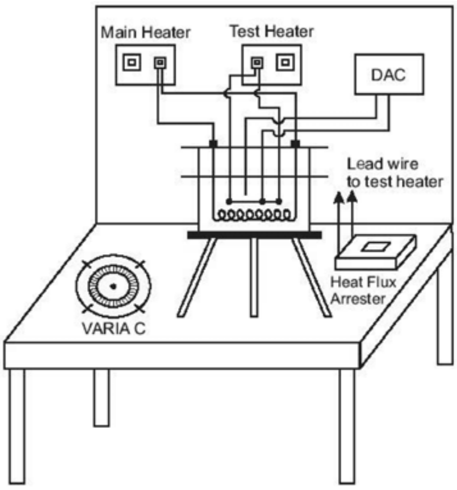


Fig. 2 Experimental set up.

The experiments were performed by increasing the electric power supplied to the wire heater (test wire). The electric power/heat input was increased in small steps using the variac until critical value is reached, at which point the heater was instantaneously broken due to increased resistance. This peak value was recorded in the digital wattmeter with peak value locking arrangement. The CHF was calculated using data obtained just before the steep increase of heater résistance. All tests were performed under atmospheric pressure. Data from all tests were deduced using the following equations. The voltage and electric current supplied to the NiCr heating wire heater are used to compute the heat flux as:

$$q = \frac{VI}{A} = \frac{VI}{\pi dL} \tag{4}$$

The main sources of uncertainty of the applied voltage and current are due to contact resistance between the wire heater and electrodes connected with only mechanical clamps. In addition, there is uncertainty associated with the length and diameter of the NiCr wire heater. The experimental uncertainty mainly including the parameters like applied voltage and length of the wire was calculated using the following relation proposed by Holman [6].

$$U_{q_{CHF}} = q_{CHF}\left\{\left(\frac{U_{V\max}}{V_{\max}}\right)^2 + \left(\frac{U_{I\max}}{I_{\max}}\right)^2 + \left(\frac{U_D}{D}\right)^2 + \left(\frac{U_L}{L}\right)^2\right\}^{\frac{1}{2}} \tag{5}$$

The uncertainties of the applied voltage and the length of wire heater are less than 3.96% and 0.7%, respectively. From the above analysis, the maximum uncertainty for pool boiling CHF was estimated to be 4.96%.

Results and Discussion:

Pool boiling experiments indicated that using nano fluids, instead of pure water as a cooling liquid, significantly increases the CHF. Fig. 3 shows the measured CHF values of CuO nanofluid at different volume concentrations expressed in percentage, compared with pure water. Significant CHF enhancement is observed for all the range of volume concentrations nanofluids, up to 130%. This is in consistent with the findings of Das et al. [3] and Bang and Chang [7].

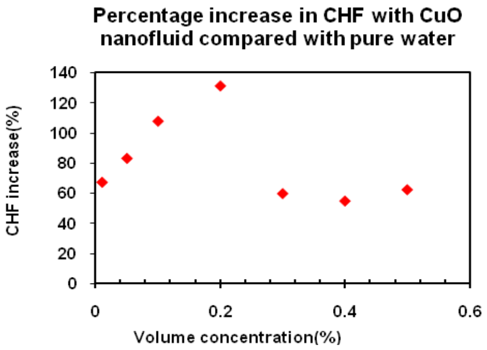


Fig 3 Percentage increase in CHF with CuO nanofluid compared to pure water

For nano-fluids with a minimum concentration of 0.01% used for the pool boiling experiment, the CHF was enhanced by 70% of the value of pure water while the CHF sharply increased up to 130% of the value of pure water at particle concentrations of 0.2 %, and then became saturated at about 60% at 0.3% onwards. Similar saturation phenomena were reported by You et al. [8] from the results of pool boiling CHF experiments of water- CuO nano-fluids under reduced pressure.

Significant CHF enhancement is observed in this work also, as shown in Fig. 4, but there are quantitative differences with the results from other researchers due to the variation of experimental parameters, such as the material and dispersion conditions of the nanoparticles, particle size as well as the heater geometry, all of which can affect the CHF.

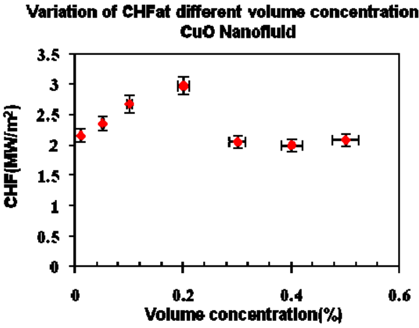


Fig 4 Variation of CHF at different volume concentrations of CuO nanofluid

The results of the present study clearly shows CHF enhancement is possible by the usage of nano-fluids instead of pure water as a cooling liquid. Further, surface coating of the heater surface is dependent on the particle concentration of the nano-fluids paving way for porous layer build up which may either increase or decrease the surface roughness depending on porosity and particle size.

The deterioration of nucleate boiling may be due to surface effect. Surface roughness measurement of the test wire exposed to three continuous cycles of heating revealed that the roughness decreases with aging. The result from the roughness tester, "Surf Test" is shown in Figure 5 for 0.01% of CuO nanofluid subject to three heating cycles. Most probably this happened due to the accumulation of nanoparticles in the porous layer formed due to boiling induced precipitation of nanoparticles.

The detailed study of the SEM image clearly showed deposition of the nano-particles on the wire surface. Figure 6 corresponds to the SEM image of the bare heater surface while; Figure 7 and Figure 8 show the SEM images at concentrations of 0.01% and 0.4% respectively. It can be observed that the deposition is more pronounced on the heater surface with 0.4% of CuO nanofluid. The presence of a porous layer on the surface definitely plays major role on boiling heat transfer through changes in roughness and wettability.

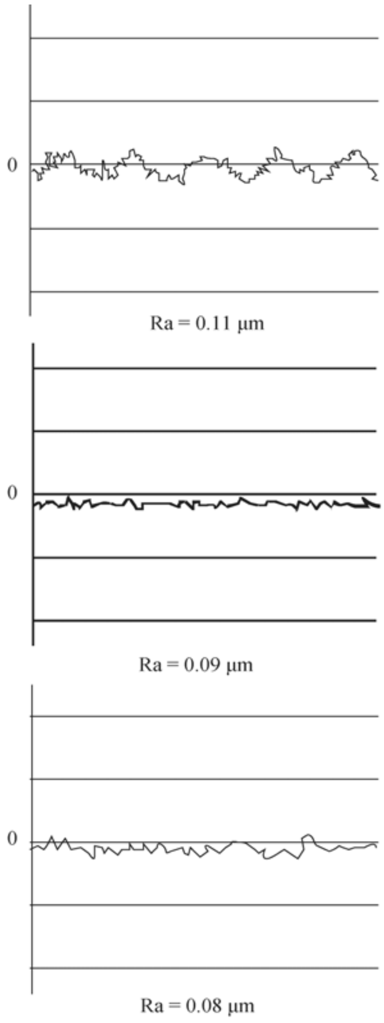


Fig 5 Decrease in surface roughness of the test wire exposed to three heating cycles (0.01% concentration) before critical value (Horizontal scale: 2.5 mm, Vertical scale: 0.1 μm).

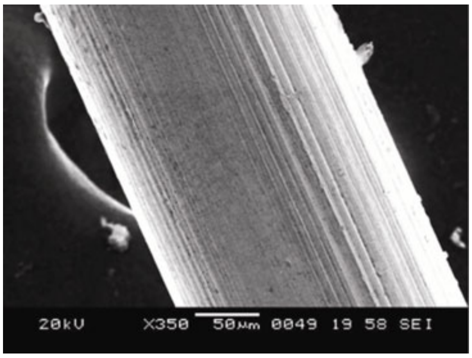


Fig 6 SEM image of bare heater surface

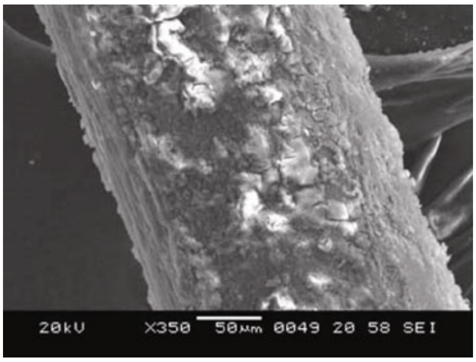


Fig 7 SEM image of heater surface with 0.01% by volume of CuO nanofluid

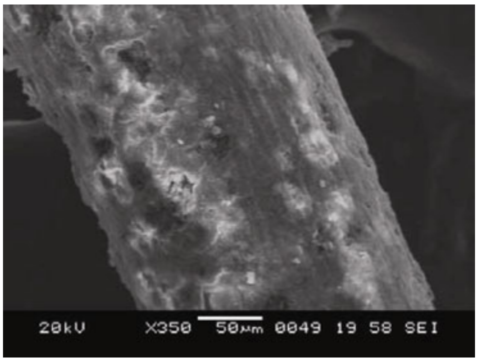


Fig 8 SEM image of heater surface with 0.4% by volume of CuO nanofluid

Conclusions

Pool boiling CHF characteristics in nano-fluids were investigated with five volume concentrations of CuO nanofluid ranging from 0.01% to 0.5%, and the effect of nanoparticle concentration in pool boiling CHF enhancement was studied experimentally.

During the experimentation, the pool boiling CHF of CuO nanofluids on a bare heater of NiCr wire was enhanced to ~130% compared to that of pure water at 0.2% nanoparticle concentration. It was observed that with low concentration of CuO the dispersion was homogeneous while higher concentrations of CuO resulted in the formation of coating over the heater surface and fouling of the vessel inner surface.

Surface roughness of the heater surface exposed to three measured heating cycles showed surface modification. This means CHF enhancement of nano-fluids was closely related to the surface microstructure and enhanced topography resulting from the deposition of nanoparticles. Evidently, nanofluids have great potential for heat transfer enhancement and are highly suited to application in practical heat transfer processes. This gives an opportunity for engineers to develop highly compact and effective heat transfer equipment.

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