Experimental investigation on the critical heat flux of Cu-water, Al-water nanofluids for precise cooling of electronic systems

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Abstract. In recent year’s huge development has taken place in the fields of integrated circuits technology and high speed processors. The performance of such electronic system is highly affected by heat generated during the operation. These heat generated on the electronic systems has to be dissipated in order to increase the performance and to avoid the damage due to high temperature resulting from heat generation. The increase in temperature may be reduced by the use of effective heat transfer devices such as heat pipes. The maximum heat transfer limits of the heat pipes are restricted by their heat flux limit. Critical heat flux (CHF) defines the maximum heat transfer limit. To meet the high demand of cooling in electronic industries, enhancement in critical heat flux limit of heat pipes as well as heat transfer surfaces are essential. Therefore in order to identify the ways to enhance the critical heat flux limit, series of experiment were conducted using two different types of nanofluids such as Cu-water and Al-water suspensions. For each nanofluids four different concentration were tested (0.0005wt%, 0.001wt%, 0.005wt%, 0.01wt %). There are two different type of wires were used to study the CHF. Ni-Cr wire with diameter of 0.19mm and 0.119mm, SS wire with the diameter of 0.08mm were used. The critical heat flux of Al-water and Cu-water Nanofluids is improved up to 124 % and 164 % respectively when compared with DI water.

1. Introduction

Precise electronic systems and high end computer processors needs more attention on the effective heat dissipation for higher efficiency, higher speed operation and to avoid undesirable damages. The heat dissipation capability using the conventional cooling methods is not sufficient for high end electronic systems and high speed processors. Use of heat sinks, air blast cooling, liquid cooling and heat pipe technology are different cooling methods evolved during the recent days. The performance of the heat pipe is better compared to the conventional cooling methods. In heat pipe technology, the heat transfer properties depend on many factors such as properties of the fluid used, physical dimension, and the properties of material used[1–3].

Cooling of electronic component can be achieved by using devices such as heat pipes, vaporchamber, micro channel etc. is using a boiling heat transfer phenomenon, which exploits the latent heat of vaporization during the liquid-to-gas phase change. CHF (critical heat flux) is the maximum heat flux where boiling heat transfer sustains its high cooling efficiency. When a surface reaches CHF, the system temperature will rise due to the resistance increase by the formation of vapor slugs. This rise in temperature leads to a system collapse by exceeding the limits of its constituent materials, So it is necessary to study the margin of heat flux to be used for cooling applications without any damages or collapse of electronic chips especially heat transfer devices such as heat pipes are used to dissipate the heat. Recent literatures show nanofluids are having the capability of improving the CHF.
An innovative fluid which contains nano-sized solid metal particles to improve the heat transfer is achieved by Choi[4]. Enhancements of thermal conductivity using nanofluids are presented in recent articles. Eastman et al.[5] also reported on the effect of thermal conductivity enhancement using nanofluids. Liu et al.[6] reported that there is 12% thermal conductivity enhancement for 0.01 volume fraction of CNT-synthetic engine oil, and 33% thermal conductivity enhancement for 0.02 volume fraction of CNT-ethylene glycol combination. Liu et al. [7] presented the enhancement of the thermal conductivity of water in presence of copper using the method of chemical reduction. They observed that the thermal conductivity was enhanced by 23.8% for Cu-nano-particles at a volume fraction of 0.001. From these articles it is proven that the nanofluids have higher thermal conductivities compare with the commercial fluids. So it is expected that the nanofluids exhibit a higher heat transfer properties especially in boiling heat transfer studies.

Das et al. [8] conducted an experiment to study the pool boiling heat transfer using a horizontal heater and nanofluids with 1 to 4% volume fractions of aluminium oxide nanofluids. Unexpectedly it was found that there is degradation in boiling performance when the particle concentrations were increased. Liu et al. [9] conducted an experiment to understand the sorption and agglutination phenomenon of nanofluids and nanoparticles-suspensions and their effects on pool boiling heat transfer. This study reveals that an agglomerated particle settles over the heater surface and forms a thin thermal resistive layer which leads to increase in critical heat flux. Bang et al. [10] conducted an experiment using a smooth horizontal flat surface and found there is a reduction in nucleate boiling heat transfer and increase in critical heat flux when using aluminum oxide-water nanofluid. This similar phenomenon was observed by Das et al. [8] also.

Recently there are few articles[11–13] published related to enhancement of critical heat flux and the mechanism for enhancing critical heat flux. Vassallo et al. [11] conducted an experiment to measure the CHF in atmospheric pressure using silica nano-solution with Ni-Cr heater wire. The measured CHF were compared with CHF of water. They were found that the 50 nm silica solution allows a maximum heat flux about 3 times that of pure water and nearly twice that allowed with the 3μm silica solutions. Kim et al. [12] studied the pool boiling characteristics of dilute dispersions of alumina, zirconia and silica nanoparticles in water. They observed that there is a CHF enhancement for all nanofluids, up to 52% with alumina nanofluids, up to 75% with zirconia nanofluids and up to 80% for silica nanofluids.

Possible mechanisms of thermal nanofluids on enhanced critical heat flux were suggested by Wen et al. [13]. They found that the CHF increased due to structural disjoining pressure and could increase the wettability and inhibit the dry patch development. Park et al. [14] presented a 200% enhancement of CHF using multi walled carbon nanotubes for 0.001% volume concentration compare with water. Effect on particle concentration, size and type on critical heat flux experimentally at saturated conditions were studied by Golubovic et al. [15]. They used two different type of nanofluids are Al₂O₃ and BiO₂. The critical heat flux can be increased up to 50% when Al₂O₃ nanoparticles are suspended in pure distilled water and 33% when BiO₂ particles are suspended. Few investigators [16–18] were studied the boiling heat transfer phenomenon using different refrigerants.

From these above literatures it is understood that, there are nanofluids which are having high critical heat fluxes are existing. The proposed work was conducted to explore different type of nanoparticles which are having high boiling characteristics and high critical heat flux values. In this paper there are two different kinds of nanofluids were used to investigate the CHF are copper and aluminium. The CHF enhancement on the effect of surface enhancement during the boiling process was also studied by coating the heater wire with nanoparticles.

2. Preparation and characterization of nanofluids
Copper nano-particles of 99.5% purity, Aluminum particles of 99.9% purity were prepared using laser evaporation process by NaBond technologies have been used for the present study. Particle-size was viewed using Scanning Electron Microscope (JEOL make) and was observed that the nanoparticle contains the particle size range of 80 to 130nm (see Figure 1). Both copper-water and Al-water nanofluids suspensions are prepared by using Ultrasonic processor- UP400S manufactured by Hielser
Tech. De-ionized water with 0.0005, 0.001, 0.005, 0.01 weight % of copper nanoparticles were subjected to sonication for about 30 minutes. The copper particles were dispersed completely after a few minutes of sonication which can be seen by the change of the color. This nanofluid suspension remains stable for about 30 hours.

![Figure 1. Size range of nanoparticles](image)

3. Experimental apparatus and procedure

Figure 2 shows the schematic diagram of the experimental set up and it consists of 1 liter capacity glass container, a Teflon cover, pre-heater, reflux condenser and two copper electrodes with the diameter of 10 mm. The two copper electrodes are placed at a distance of 70 mm apart with the support of Teflon cover and this Teflon cover act as a closure for the container. The pool temperature was measured using T-type thermocouple. The experiment was started with a constant temperature with a help of a pre-heating arrangement as shown in Figure 2. To avoid the vapor losses during the experiment, a reflux condenser was mounted over the Teflon cover and was cooled with external water supply. So the volume concentration of the working fluid did not change during the experiments. A Ni-Cr wire with the diameter of 0.19 mm was horizontally connected with the two electrodes. After each CHF experiment, the wire was examined using scanning electron microscope (SEM) to see if any nanoparticle deposition on the wire surface. The electrodes were connected to a DC power supply (120 V/18 A). A data acquisition system was used to measure the temperature data.

After maintaining the pool temperature constant, the power was given to the electrodes. The power was increased with a small increment ≈1 watt at a constant interval up to the CHF occurs. The experiment was stopped when instantaneous breakage of the wire occurs. The CHF was calculated using data obtained immediately before the steep increase of wire resistance or before the breakage of wire.

The CHF was calculated by

$$ q_{CHF} = \frac{VI}{\pi DL} $$

(1)

where V is voltage applied and I is the current.
4. Results and discussion
In order to analyze the results, the effect of preheating, time interval between pulses, kind of nanofluids, nanoparticle deposition and the effect of wire diameter on the CHF are recorded.

4.1. Effect of preheating on the CHF
To study the effect of pre-heating on the CHF, experiments were conducted at different pre-heating temperatures such as 27, 40, 50 and 60°C as well as without pre-heating condition using the nichrome wire with the diameter of 0.19 mm. Firstly, experiment was done with water and it was observed that CHF was reached much earlier in preheating case than in the case of without preheating. Also CHF was found to be highest at room temperature and lowest in the saturation temperature of 60°C. Further it can be seen that the increase in the preheating temperature decreasing the CHF linearly as shown in Figure 3. The maximum enhancement in CHF was found to be 157% at low pre-heating temperature. CHF values at room temperature and at saturation temperature are taken as standard to compare with CHF values of nanofluids. For both the nanofluids experiments were done only at room temperature and at saturation temperature for all the four different concentration of nanoparticle. As similar to the CHF of water, CHF of nanofluids also reached much earlier in preheating case than in the case of without preheating. In the case of aluminium nanofluids there is only 28% of increase between with and without preheating experiments using aluminium nanofluids (Figure 4).
Aluminium nanofluid has highest value of CHF at 0.005 wt % of particle in both the condition with and without preheating. CHF of aluminium nanofluids increases as the concentration of nanoparticles increases till the 0.005 wt % and then it starts decreasing. So aluminium nanofluid has its peak CHF at the concentration of 0.005 wt % of particles. This concentration was found to be the optimum concentration of the aluminium nanofluids where it achieved maximum increase in CHF.

The effect of preheating on the CHF of copper nanofluids were presented in Figure. 5 and a comparison was made with and without preheating case. For copper nanofluids CHF keeps increasing as the concentration increased in both the cases unlike in the case of aluminium nanofluid. In all these experiments bubble generation on heater in preheating case was occurred while preheating the fluid but in without preheating, the generation of bubble starts only when some voltage was supplied to the wire heater. The reason behind the effect of preheating and high critical heat flux at room temperature that at saturation temperature can be explained by the help of Newton’s law of cooling:

\[ q = h(T_w - T_f) \]  

The occurrence of CHF is accompanied by an excessive increase in the surface temperature for a surface-heat-flux-controlled system. In the preheating case the surface temperature increases as preheating starts but in without preheating case surface temperature start increasing when wire heater line was switched ON. So it is natural that more time needed to achieve CHF for without preheating case compared to preheating case as \((T_w - T_i)\) is higher in without preheating case.

4.2. Effect of time interval between pulses of CHF  
In this work all the experiments are performed by maintaining equal intervals between the readings. In order to find the effect of time interval between voltage pulses, three experiments were performed with water while varying the voltage pulses. The time interval between the pulses was varied as 1, 3 and 5 minutes and all other parameters are kept constant during this experiment. Figure. 6 shows the effect of time interval on the fluid temperature and CHF. These experiments were done with a different set up than what was mentioned (Figure. 2) earlier. Set up consists of a constant temperature water bath which replaces the flat heater. This was done to maintain a constant 60°C around the glass vessel.
Figure 6. Effect of time interval between the voltage pulses

From the Figure 6 it can be concluded that the CHF does not depend on the interval of time maintained between the voltage pulses. The CHF was found to be same in all the three cases while the temperature of the fluid was maintained constant. Therefore, it can be concluded that CHF does not depend on time interval between the pulses but depends on the temperature of the fluid or on the temperature of the heated surface.

4.3. Effect of nanofluids on CHF

The CHF of nanofluid is expected to be higher than that of water due to the fact that the thermal conductivity of the nanofluid is more than that of water. In fact, the properties and behavior of a nanofluid depend upon a number of parameters such as the properties of the base fluid and the dispersed phases, particle concentration, particle size and morphology. As it is mentioned earlier, two kinds of nanofluids (aluminum and copper) have been used find the CHF. Under this topic, CHF of water and both the nanofluids at four different concentration will be compared in with and without preheating.

For aluminium nanofluids the critical heat flux increases as the concentration of nanofluid increases till 0.005% where it reaches a maximum heat flux and after that point, the concentration of nanoparticle does not have any effect on peak heat flux. In both the cases (with and without preheating), a similar trend in CHF curve was observed. As per the literature, there is an optimum concentration of nanoparticles where CHF is maximum and after that concentration, even if the concentration increased, there will not be any effect on peak CHF. In this work the optimum concentration was found to be 0.005 wt% of particles in both case with and without preheating. In the case of no preheating, maximum increase in CHF on aluminium nanofluid was found to be 49% (Figure 7) than water and in with preheating case enhancement in CHF curve in CHF raises to 200% when compared to CHF of water (Figure 8). Figure 9 shows the CHF of copper nanofluids at various concentrations and it was found that the CHF was increasing till 0.01 wt%. A similar enhancement pattern was found in the previous studies also. The maximum increase in CHF for copper nanofluids compared with water was found to be 52% for (Figure 9) without preheating case and 140% (Figure 10) for preheating condition.

Figure 7. Comparison of CHF of water and aluminium nanofluids for without preheating case
Figure 8. Comparisons of CHF of water and copper nanofluids without preheating aluminium nanofluids for with preheating case

Figure 9. Comparison of CHF of water and copper nanofluids without preheating aluminium nanofluids for with preheating case

Figure 10. Comparison of CHF of water and copper nanofluids for with preheating case

Figure 11. SEM image of plane heater a) taken before the experiment b) after the pool boiling experiment with water c) after the pool boiling experiment with aluminium nanofluids d) after the pool boiling experiment with copper nanofluids

It was interesting to note that there was a layer of deposition was found wire heater after the test. The
heater was observed under SEM and it was found that it was layer of nanoparticles. A similar deposition was also reported in the literatures[12,16,19–21] and believed to be the most significant reason behind the enhancement in CHF with nanofluids over water. This deposition of nanoparticles on heater depends on the concentration of the particles in nanofluids. Thickness of layer increases as the concentration of nanoparticles increases in nanofluids. But this deposition can increase the critical heat only to a particular concentration, because after that increase in critical heat flux becomes saturated and thickness of layer could not affect it. The surface modifications due to nanoparticle coating are quite different according to the kind of nanoparticle dispersed in nanofluids, but not to the material of heater. The nanoparticles generate a nano porous layer on the test-section of heater surface. The presence of nano porous layer enhances the trapping of liquid in the nano porous sorption layer and prevents the vapour blankets formation. Therefore, the CHF increases with increasing the sorption layer thickness at the low particle concentration range. Decrease in active nucleation sites also helps in increasing the critical heat flux of nanofluids over the critical heat flux of water. SEM images in Figure. 11 show the deposition of nanoparticles on the test heater.

4.4 Effect of nanoparticles coating on heater

In order to study the effect of nanoparticle coating on the CHF, experiments were done with coated heater with water under preheating conditions. There are five different sample of test heaters were prepared by depositing the nanoparticles. The deposition of nanoparticle was done by preparing copper nanofluid with the concentration of 0.01 wt% and immersing the nichrome wire heaters in the nanofluid. Then after every five minutes all the samples were taken out and dried carefully. After drying a small piece of wire is taken each time for characterization and rest of the samples were again placed in nanofluid after drying. This process was repeated until all the five samples were coated. The surface morphology of the nanoparticle coated wire at different coating thickness was presented in Figure. 12(a-e).

![Figure 12. SEM Images of a) Nanoparticle coated heater with one layer b) Nanoparticle coated heater with two layers c) Nanoparticle coated heater with three layers d) Nanoparticle coated heater with four layers e) Nanoparticle coated heater with five layers](image)

After the preparation of samples, CHF experiments were conducted with all the above five samples and it was found that there is 115% increase in CHF, obtained with the heater which has two layer of coating of nanofluids as shown in Figure. 13. For all the five experiments critical heat flux value was higher than that of water but the maximum increase was found with the second heater. As the nanoparticles keep depositing on the heater the nano sorption layer also increases. But after a certain point the
thickness of the sorption layer will not increase as it gets saturated, and therefore increase in CHF will also get saturated and there will be no effect on peak CHF after that point.

Figure 13. Effect of nanoparticle coating on critical heat flux

Figure 14. Contact angle of aluminium nanofluid after testing

The coating of nanoparticle enhances the surface wettability of heater and it is resulted from the decrease in surface contact angle which is an angle between the heater surface and liquid layer of the bubble formed on the surface. Enhancement in the wettability causes contact angle to decrease and enhancement in wettability and it is resulted from a combined effects of increase in adhesion tension and increase in roughness. Adhesion tension of nanofluid is higher than that of the water. The porous layer increases the effective contact area, thus roughness factor will be more than unity. Both these effects can decrease the contact angle significantly. For instance the contact angle of water was 90° and for aluminium nanofluid it was decreased to 56.17° as shown in Figure 14. As result, bubbles will have less time on the boiling surface and the radius of bubbles at the point of departure will be smaller. This can translate into an increase in the peak heat flux.

From the above results it is clear that the addition of nanoparticle in to the traditional fluids increases the CHF. Also found that the thin deposition layer formed by the nanoparticle layer also enhances the CHF significantly. These results suggests that the coating on the cooling surfaces or coating the evaporator of heat pipes can increase the CHF leading to the higher operating range of cooling devices.

5. Conclusions

Critical heat flux is one of the most significant design criteria for heat pipes and electronic chips and is also a very important factor in economy and safety of electronic devices. Numerous studies have dealt with experimental and theoretical approaches to enhance CHF. These include changing surface chemistry and geometry. Since nanotechnology is able to produce many types of nanometer size particles, nanofluids have become innovative types of heat transfer fluids. These nanofluids are being used by most of the researchers to enhance the critical heat flux.

From this study it was seen that a significant enhancement in the CHF can be attained by using aluminium and copper nanofluids at very less concentration of nanoparticles.

The main findings of this study are as follow:

1. The CHF of nanofluids was found enhances in both cases with and without preheating conditions. For aluminium nanofluid CHF increases as the concentration of nanoparticles increases in nanofluid and reached peak value at 0.005 wt% for preheating. A maximum increase in CHF was found to be 49% and 200% respectively for with and without preheating for Al nanofluids. For copper nanofluids critical heat flux increases as the concentration of nanoparticles increases in the fluid. Maximum increase in CHF of copper nanofluids was to be 52% and 140% at 0.01 wt% for both the condition of with and without preheating case.
2. Experimental results showed that the CHF does not depend on the time interval maintained between the voltage pulses and it depends on the temperature of the heater surface and bulk
temperature of the fluid.

3. Nanoparticles deposited on heater during the experiment enhance the wettability by decreasing the contact angle which leading to the increase in CHF. The nano porous layer formed on heater decreases the active nucleation sites and decreases contact angle. Number nucleation sites and lower contact angle on the surface of heater was the significant reason behind the remarkable increase in CHF of nanofluids.

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