Pool Boiling Heat Transfer and CHF enhancement of Aqueous Al₂O₃ and CuO Nanofluid

Abhishek, Prakhar Chaturvedi, Syed Mohd Yahya and Taliv Hussain
Department of Mechanical Engineering, Aligarh Muslim University, Aligarh, India.

Corresponding author: cprakhar.18@gmail.com

Abstract. In this study, experiments are performed to understand the critical heat flux (CHF) enhancement using nanofluids, with special emphasis on pool boiling. Al₂O₃ and CuO nanoparticles were purchased from Sisco Research Laboratories (SRL) having particle size of ~25 nm and ~40 nm respectively. The critical heat flux measurement at atmospheric pressure for three different concentrations (0.01gm/lt, 0.1gm/lt and 1gm/lt) of Al₂O₃ and CuO nanoparticles suspension in water was taken and pool boiling experiment was carried out at atmospheric pressure using 0.111mm Nichrome wire submerged in each solution. The significant enhancement in CHF has been recorded with each of the nano solutions as compared to the pure water. With increasing the concentration of thenanoparticles the CHF was found to increase as compared to deionised water.

1. Introduction
The boiling process in which the heater surface is submerged in a stagnant liquid body at saturation condition is called pool boiling [1]. In pool boiling phenomenon, boiling occurs due to buoyancy effect. This involves the formation of vapour bubble, bubble growth and departure from the heating surface. Boiling heat transfer has a peak heat flux below which a boiling surface can stay in the nucleate boiling regime. This is called the critical heat flux (CHF), and it is the point beyond which there is a transition from a nucleate boiling regime to a film boiling regime under pool boiling. This transition is an undesirable phenomenon, causing an excessive increase in the temperature of the boiling surface. Such an increase in temperature can exceed the melting point of the construction material and lead to a crisis in various thermal systems, such as boilers and fuel in a nuclear reactor. Thus, an enhanced CHF is very important to the safety margin of a thermal system. To enhance the CHF considerable researches are currently underway. From the previous studies of CHF it can be seen that dispersing small amounts of nano sized particles of metals (e.g., gold, silver, platinum) and metal oxides (e.g., alumina, titania, silica ) in base fluid (e.g, water, ethylene, oil, polymer solution) the CHF can be increased significantly [2]. These fluids originally attracted more interest because of their extremely enhanced thermal conductivity [3,4]. Properties of nanofluids that have been discovered include high thermal conductivity and a significant enhancement in nucleate boiling critical heat flux at very low concentrations of nanoparticles [2-8]. Alumina and copper attracted many researchers due to their good thermal, electrical and mechanical properties [12].

In this work, the study of CHF has been done using Al₂O₃ and CuO nano particles with water as base fluid in pool boiling environment, and the boiling curve for water and nanofluids were plotted showing different regimes of boiling.

2. Preparation of Nanofluids
In the case of two-step method nanoparticles are firstly prepared in a form of powders by physical or chemical methods, e.g. grinding, laser ablation, sol-gel processing, etc. and then suspended in base fluid. This method of production is cheaper because nano powders are produced on large scale.
Therefore, in order to prepare a stable nano suspension, sonication process as well as addition of stabilizers may be required. The two step method applies better for nanofluids containing oxide nanoparticles. In this paper, the nanoparticles chosen are Al$_2$O$_3$ and CuO, because they are chemically more stable and their cost is less than their metallic counterparts and are also easily available. Al$_2$O$_3$ and CuO water nanofluid is prepared by two step method. The Al$_2$O$_3$ and CuO nanofluids were produced by dispersing the mentioned nanoparticles into the base fluid, distilled water. The Al$_2$O$_3$ and CuO nanoparticles were purchased from Sisco Research Laboratories, India and had a spherical shape with a mean diameter of 25 nm and 40nm respectively. Prior to each test, the Al$_2$O$_3$, and CuO nanofluids were processed in an ultrasonic bath as shown in Figure 1 for 90 minutes to break any possible aggregations of nanoparticles and to keep the nanofluids uniformly dispersed. No surfactant was used in the formulation to avoid any complication in interpreting the experimental results.

| **Nomenclature** | **subscripts** |
|------------------|----------------|
| q” | Heat flux [W/m$^2$] |
| A | Area of heater wire [m$^2$] |
| I | Current [Ampere] |
| V | Voltage [Volt] |
| D | Wire diameter [m] |
| L | Length of test heater wire [m] |
| K | Constant |
| Hfg | Enthalpy of vaporisation [J/kg] |
| Cp | Specific heat [J/kg$\cdot$K] |
| H | Heat transfer coefficient [W/m$^2$$\cdot$K] |
| T | Temperature |
| P | Density [kg/m$^3$] |
| $\Sigma$ | Surface tension [N/m] |
| Csf | Constant |
| CHF | Critical heat flux |
| Pr | Prandtl number |

![Figure 1. Ultrasonicator](image1.png)

![Figure 2. Set up for critical heat flux experiment](image2.png)
3. Description of pool boiling experiment

The apparatus consists of a cylindrical glass container housing the test heater and a heater coil for the initial heating of the water. This heater coil is directly connected to the mains (Heater R1) and the test heater (Nichrome wire) is connected also to mains via a dimmer-stat. An ammeter is connected in series while a voltmeter across it to read the current and voltage, respectively. The glass container is kept on an iron stand which could be fixed on a platform. There is provision of illuminating the test heater wire with the help of a lamp projecting light from behind the container and the heater wire can be viewed through lens. The schematic arrangement of the apparatus is shown in Figure 2. This experimental set up is designed to study the pool boiling phenomenon up to critical heat flux point. The pool boiling over heater wire can be visualized in the different regions up to critical heat flux point at which the wire melts. The heat from the wire is slowly increased by gradually increasing applied voltage across the test wire and the change over from natural convection to nucleate boiling can be seen.

The formation of bubbles and their growth in size and number can be visualized, followed by the vigorous bubble formation and their immediate carrying over to surface and ending thus in the breaking of the wire indicating the occurrence of critical heat flux point. This is repeated for various temperatures of the water in the container up to the saturation temperature.

In the experiment the values of current, voltage and heater surface temperature recorded till the wire breaks and the heat flux through the wire is calculated by the equation:

\[ q'' = \frac{IV}{\pi DL} \]  \hspace{1cm} (1)

Where D is diameter of test wire which is 0.111mm and L is the length of test heater wire which is 100mm. Although a number of researches have considered various theories of CHF. Kutateladze [10] proposed that near the critical heat flux condition the meaning of bubble generation and departure is lost and it was a hydrodynamic phenomenon. He proposed the correlation.

\[ q'' = Kh_{fs} \left[ \frac{\sigma g (\rho_s - \rho_v)}{\mu} \right]^{1/4} \]  \hspace{1cm} (2)

In this equation K is a constant and from the experimental data Kutateladze calculated the value of K, which is 0.16. Further Zuber [11] proposed the correlation similar to the Kutateladze by considering the dynamic effect of vapor jet is important. The zuber correlation is given as

\[ q'' = Kh_{fs} \mu^{1/2} \left[ \frac{\sigma g (\rho_s - \rho_v)}{\mu} \right]^{1/4} \]  \hspace{1cm} (3)

The value of K ranges from 0.157 to 0.138. Further from experiments Zuber proposed the value of K=0.131. The value of K depends on the heater surface and geometry.

Rosenow [9] gave a relation of CHF and surface superheat \(T_w - T_{sat}\) which is:

\[ q'' = \mu h_{fs} \left[ g (\rho_s - \rho_v) / \sigma \right]^{1/2} \left[ \frac{C_{pl} (T_w - T_{sat})}{C_{ef} h_{fs} \Pr_f} \right]^{3/4} \]  \hspace{1cm} (4)

Where \(C_{ef}\) is a constant which depends on the geometry of the surface.
4. Results and Discussion

4.1. Pool boiling results of water.
To check the reliability of the apparatus the three consecutive trials on water were taken. All the data points are clustered closely as shown in the Figure 3 which shows good repeatability of experimental procedure and apparatus. To depict the different regime of pool boiling curve one trial of the three consecutive tests had been taken for consideration. From the experimental data of pool boiling of pure water the calculated CHF value is consistently close to the Zuber correlation CHF value (1.26MW/m²), which is calculated by Eq 2, in which the value of constant K is 0.149 and the mean absolute error is about 14%.

![Figure 3. Boiling curve for pure water for three consecutive trials](image1)

From the experiment it was observed, initially when the wire temperature was very low the heat transfer occurred by natural convection and with increasing heat flux the wire temperature also increased and small sized bubbles formed at the nucleation site. Further increasing the heat flux the frequency of bubble formation and the size of bubbles increased. The bubbles rising up to the liquid surface with increasing heat flux covered the heater surface and restricted the heat transfer. Due to this there was an excessive rise in temperature and on further increasing the heat flux the wire started burning.

4.2. Pool boiling results of Al₂O₃-water nanofluids
From the above boiling curves (Figure 4) the CHF enhancement using alumina nanopowder has been investigated. For 0.01gm/lit alumina-water solution the sudden increase in temperature is recorded just after 1522 KW/m² where the wire burning starts, thus it is CHF value for this concentration. In comparison of di-ionized water CHF is ~31% more for this solution. Similarly for the other two concentrations 0.1gm/lit and 1gm/lit the CHF enhancement is ~45% and ~66% respectively as compared to deionised water.

4.3. Pool boiling results of CuO-water nanofluids
From the curves (Figure 5) it has been found that for 0.01gm/lit CuO-water solution, for heat flux value above 1415 KW/m² the sudden increase in wire temperature is seen and wire burning start thus it is the CHF for this solution, this CHF value is ~22% more than the CHF for di-ionized water. Similarly for concentrations 0.1gm/lit and 1gm/lit the CHF enhancement is ~61% and ~82% respectively as compared to deionised water.
The effect of different nanoparticles and their concentrations is shown in the Figure 6, which indicates that for both types of nanoparticles CHF increases with increase in concentrations. It also shows that for low concentrations alumina gives better results and for high concentration CuO gives better results.

**Figure 4.** Boiling curves for three different concentrations of Al₂O₃-water nanofluids

**Figure 5.** Boiling curves for three different concentrations of CuO-water nanofluids
5. Conclusions

The results showed that when the thin liquid micro-layer underneath the vapour bubble gets evaporated, nanoparticles are left behind on the heater surface, thus a porous layer of nanoparticle developed over the heater surface. This porous layer supplies liquid to the dry spot on heater surface by capillary action which delays the burn out point and increases the surface wettability and maintain the surface roughness which are responsible for CHF enhancement. The nanoparticle deposition over the heater surface increases the nucleation site density which decreases the bubble departure diameter, due to this bubble coalescences decreases which reduces the vapour blanketing. Also with decreasing the bubble departure diameter the frequency of bubble departure increases which increases the wettability of surface which is responsible for CHF enhancement.

6. References

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