Determination Of Critical Heat Flux In Pool Boiling Using ZnO Nanofluids

Sagar C. Hiswankar 1, Jagdeep M. Kshirsagar 2

1 PG student, Maharashtra Institute of Technology, Aurangabad (India).
2 Associate Professor, Department of Mechanical Engineering, Maharashtra Institute of Technology, Aurangabad (India).

Abstract

CHF creates inconvenient compromises between economy and safety in most industries, related to thermal systems such as nuclear power plants. In this study, pool boiling experiments were performed with water based nanofluid with Zinc Oxide nano particles from various concentration of 0.01 volume percent (v%) to 0.0001 volume percent (v%) on an electrically heated Ni-Cr wire of 0.4 mm diameter at atmospheric pressure. The results showed that the water-based nano-fluids significantly enhanced CHF compared to that of pure water. The CHF values of the ZnO nano fluids were enhanced from approximately 70% to 80% of pure water. During the test it is found that, a sizable layer of nano particle deposits formed on heater surface. The CHF enhancement using deposition of nano particles are related to surface wettability of the heating surface during pool boiling. It is supposed that CHF enhancement in pool boiling of nano-fluids is mainly caused by the nanoparticles coating of the heating surface.

Keywords: Nano-fluids; Nanoparticles surface coating; Pool boiling; Critical Heat Flux (CHF), Nickel-chromium (Ni-Cr). Deionized water (DI)

1. Introduction

Nucleate pool boiling phenomenon is very effective & efficient mode of heat transfer, due to its ability to transfer large amounts of heat with relatively small temperature differences. Conventional and enhanced boiling of liquids have a wide range of industrial applications that include power generation, chemical and petrochemical industries, air conditioning, refrigeration and cryogenics, metallurgical quenching process, desalination of seawater and in nuclear power plants, either for heating or electricity generation. Recent applications of boiling heat transfer in cooling of electronics devices show many promises.

At present, the whole world pays great attention to energy efficiency improvement and environmental protection due to global warming caused mainly by excessive use of fossil fuels. One of the fundamental ways of alleviating global warming is to increase the efficiency of the boilers in power plants, evaporators in refrigeration system, and various heat exchangers for commercial and domestic use. Especially, nucleate boiling heat transfer occurs in many of these heat exchangers and hence while incorporating this, it is imperative that CHF should not exceeded.

CHF in pool boiling is defined as the peak heat flux under which a boiling surface can sustain nucleate boiling. On attaining the CHF, transition from nucleate boiling regime to film boiling regime occurs, which is undesirable and causes temperature of the heated surface to reach the melting point, so that it creates inconvenient compromises between economy and safety in most industries, related to thermal systems. Therefore, an enhanced CHF is advantageous not only for increasing the safety margin of the thermal system, but also to design compact and efficient cooling systems required for electronic devices, nuclear and chemical reactors, air conditioning, etc. Therefore, much effort has been focused on clarifying the mechanism underlying CHF occurrence and improving the CHF through the using nanofluids.

You et al. [1] showed 200% enhancement in CHF for copper heater immersed in Al₂O₃-water nanofluid. Vassallo et al. [2] conducted CHF experiments in pool boiling indicating some possible surface interaction between wire and nanoparticles because of silica coating of 0.15 – 0.2 mm observed at the end of experiment. Bang and Chang [3] showed that CHF enhancement due to change in surface characteristics like surface roughness and nucleation site density by deposition of nanoparticles. Madhushree Kole [10] observed ~117% CHF enhancement at 2.6% volume concentration of ZnO in ethylene glycol Nanofluids. This enhancement is attributed to thin layer nonmaterial on constantan wire heater. Same result is obtained for Fe₃O₄ nanofluids with Ni-Cr wire heater by M. Sheikhbahai [7]. Moreno [16] reported a large enhancement in CHF by 240% with 0.5 g/L concentration of ZnO nanoparticles in aqueous nanofluids. CHF of water–Al₂O₃ nanofluids on a Ni-
Cr heater has 176% CHF enhancement at $10^3$% concentration [4]

2. Experiment

2.1 Preparation of Nano Fluid

Preparation of nano fluids is the first key step in applying nanophase particles to changing the heat transfer performance of conventional fluids. The nanofluid does not simply refer to a liquid-solid mixture. Some special requirements are necessary, such as even suspension, stable suspension, durable suspension, low agglomeration of particles, no chemical change of the fluid. In general, one of the effective methods used for preparation of suspensions is to use magnetic stirrer. This technique aims at changing the surface properties of suspended particles and suppressing formation of particles cluster in order to obtain stable suspensions. In order to ensure a stable, uniform, continuous suspension, the dispersion solutions are vibrated on a magnetic stirrer about 3 h just before the boiling test is performed.

Water-based nano-fluids can vary according to the type of nanoparticles dispersed in the water. In the present investigation, ZnO nanoparticles, which can be commercially mass-produced, were used to make the nano-fluids. The ZnO nanoparticles used in this work are produced using a sol-gel process by Nanoshell LLC Product Corporation (USA). Generally, the properties of the nano-fluid depend on the properties of the nano-particles, and the surface molecules taking part in the heat transfer procedure depend on the size and shape of the particles themselves, which are also affected by the agglomeration of the particles. As shown in the figure 1 taken by transmission electron microscopy (TEM), the size has a normal distribution in a range from 80 nm to 200 nm (50 nm avg. diameter is given from the manufacturer). Characterization was done by X-ray diffraction measurement in $\theta$–$2\theta$ configuration in the range of $10^\circ$–$80^\circ$. The graph shown in Figure 2 depicts the X-ray diffraction spectra has highest intensity of 9177 counts at 36.39$^\circ$. It is also observed that all zinc nanoparticles remained in pure zinc state.

It is known that the flow phenomenon of a liquid–solid solution depends on the hydrodynamic force acting upon the surface of solid particles. Therefore, volume fraction of the solution is considered a more important factor than mass fraction. Also, the following conversion formula is used conventionally, as it is very difficult to measure the precise true volume of nanoparticles.

$$\phi_v = \frac{1}{1 + \left(1 - \phi_m\right) \frac{\rho_p}{\rho_f}}$$

Where $\phi_m$ is the mass concentration of nanoparticles, $\rho_p$ is the nanoparticles density and $\rho_f$ is the fluid density, and $\phi_v$ volume fraction.

An electronic scale with accuracy of 0.0001 gram is used weighting proper amounts of ZnO nano powder. The nanofluids were prepared at varying concentrations: 0.01%, 0.001%, 0.0001%, by volume. The corresponding mass fraction for using proper amount of nano powder is determined by the equation (1)
The reflux calculated by Eq. (r than that s increased in ll steps. The resistance of =mp 0
s initially increased in large saturated ion, the measured CHF s performed by –e compared in-
olt s maintained at the s⁰ fg all with re performed e first

The experiment i diameter (m) and the wire length (m),
input current (A
of the Ni
power i
the electric power supplied to the wire with
the experiment i
and heated by the
and a 100 mm length,
experiment. An Ni–Cr wire with a 0.4 mm diameter
and a 100 mm length is used as the heated surface
and heated by the AC power supply with a 230 V, 50
A. The signals of the voltage, the current and the
temperature are measured with a National Instrument
data acquisition system.

All pool boiling experiments are performed after
the working fluid is maintained at the saturated
temperature (100 ± 0.5°C) and atmospheric pressure.
The experiment is performed by gradually increasing
the electric power supplied to the wire with a regular
pattern. The power is initially increased in large
steps. When the expected CHF value is reached, the
power is increased in small steps. The resistance of the
Ni–Cr wire sharply increased, and the wire became red-hot or broken suddenly when the CHF
occurred. The CHF is calculated by Eq. (2) using
the data obtained immediately before the sharp increase
of the Ni–Cr wire resistance.

\[ q'' = \frac{V \times I}{\pi D L} \]  \hspace{1cm} \text{.......... (2)}

Where V is the inputted voltage (Volt), I is the
input current (Amp), and D and L represent the wire
diameter (m) and the wire length (m), respectively.

The pool boiling CHF experiments are first
performed with DI water, for validation of the experiment. To validate the repeatability of the experimental results, the experiments are performed
more than 5 times. In addition, the measured CHF values are compared with the results of Eq. (3),
known as the Zuber’s CHF correlation [14], which
has been widely used to predict the pool boiling CHF
for pure water at 1 atm. Pressure. The averaged experimental result (1090 kW/m²) agrees well with
the predicted value (1144 kW/ m²) within approximately 5%.

\[ Q'' = \frac{\pi}{4} \rho h f g \left[ \frac{g \sigma (\rho_f - \rho_g)}{\rho_g^2} \right] \frac{1}{4} \hspace{1cm} \text{.......... (3)} \]

where \( Q'' \) is the heat flux, \( \rho_f \) and \( \rho_r \) are the gas
density and the fluid density, respectively, \( h_f g \) is the
latent heat of vaporization, \( g \) is gravitational
acceleration, and \( \sigma \) is the surface tension.

2.4 Experimental Uncertainty

Considering the uncertainty in calibration, the
uncertainty in heater surface temperature measurement was ±0.5 K. The total nucleate boiling
heat flux uncertainty (considering uncertainties in
voltage, current, and heater surface area) is estimated
as less than 5%.

3. Results and discussion

In the experiment it is observed from, figure 4 and
figure 5, that, CHF for nanofluids is greater than that
of base liquid. Figure 4 shows the measured CHF for
nanofluids with different volume fractions of
nanoparticles and comparison with DI water. The
maximum CHF enhancement was about 80%
ho-fained for nano fluid containing 0.01% (by volume)
of ZnO nanoparticles. This observation is similar to
that reported for many different types of Nano-fuids.

![Figure 4 CHF for nano fluids with different volume fraction](image-url)

A close look at the wire surfaces at the end of
the boiling experiments reveals that the surfaces get
coated with a thin layer of material. This is consistent
with the mechanism proposed by Kim et al. [15] that

the nano-coatings formed during nanofluid boiling are created as the vapor bubbles’ micro layers evaporate; leave behind the nanoparticles which then bond to the hot heater surface. Presence of this thin layer indicates a change of heater wire surface morphology between the start and the end of the boiling experiments. Figure 6 a and b show the scanning electron micrographs of the wire surface after CHF experiments in DI and nanofluid containing 0.01% volume fraction of ZnO nanoparticles respectively. It is clearly observed that the wire surface after boiling in the nanofluid develops more number of dark dots, compared to that after CHF measurements in base fluid DI water. Increasing number of dark dots on the wire surface indicates increasing surface roughness with more peaks and valleys and is responsible for the observed CHF enhancement. As from figure 6 (a) and figure 6 (b), it may be noted that the coating crumbles off when it is dry indicating that they are weakly bound to the wire surface.

Figure 6. SEM pictures of the wire surface after CHF experiments in (a) pure water (b) nanofluid containing 0.01% volume fraction of ZnO nanoparticle respectively

remain and are deposited on the heated surface after the bubbles depart from the nucleated site. New vapor bubbles then form on the surface again. The heated surfaces were changed by the deposition of nanoparticles. The deposited nanoparticles generated a porous layer on the Ni–Cr wire, which can improve the wettability of the wire. In other words, it is easy to rewet the hot spots and to cool the heated surface. This rewetting capability enhances the CHF of the Nanofluids. Furthermore, the degree of CHF enhancement increased as the amount of deposited nanoparticles increased. Therefore, the CHF was more enhanced at higher nanoparticles concentrations.

4. Conclusion
In this study, the characteristics of CHF enhancement using ZnO Nano fluid are investigated experimentally. The main findings of this study are as follows:
(1) In the pool boiling experiments, considerable amounts of nanoparticles are deposited on the wire. Thus, the surface wettability, which is important parameter for CHF enhancement, is changed and the CHF is also enhanced.
(2) The CHF measured using a thin Ni-Cr wire display appreciable increase with increasing ZnO concentration and reaches a maximum of 80% corresponding to 0.01% volume fractions of ZnO nanoparticles.

5. References
[6] Hyungdae Kim, Jeongbae Kim, Moo hwan Kim “Experimental study on CHF characteristics of Water-
TiO2 Nanofluids” Nuclear Engineering and Technology, vol.38 No.1 February 2006


