Analysis of Experimental Studies on Pool Boiling Characteristics of Nanofluids

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Abstract— Among the topics of research in this area, the use of nanofluids as a heat transfer fluid has drawn much attention recently. Within the last five years work investigating the pool-boiling of these fluid has increased dramatically. However, the existing literature on the subject shows some varying results that need further investigation to interpret. An experimental study was performed studying the behavior of gold nanofluids during pool-boiling. In these experiments it was found that while the heat transfer decreased about 20% over the critical heat flux (CHF) was increased 2.8 times for the 3 nm sized particles. For 15 nm particles the CHF was increased over 3.5 times over pure water with a maximum at nearly 5 times amplification. After performing the experiments, scanning electron microscope images were taken of the surface as a deposition of nanoparticles was observed on the surface. It is this surface deposition that is the source of the altered boiling curves as pure water on the nanoparticle deposited surface behaves similarly to the nanofluid curve. Also, a set of experiments were also performed using HFE 7000 where no CHF enhancement was observed. Further investigation was performed to determine the source of this enhancement including an examination of the wetting characteristics of the surface. However, using existing correlations predicting the critical heat flux it was seen that the wetting of the surface likely is not the sole source of the enhanced CHF.

Key words: Pool Boiling, Nanofluids

I. Introduction

In an attempt to resolve these issues several methods are being investigated. One area that has drawn considerable attention in recent years has been the use of nanofluids as a heat transfer fluid. The idea of using these nanofluids, defined as a solution with particles less than 50 nm in size, was first introduced by Choi [1] in 1995. Since then interest in nanofluids has grown exponentially. His and later research by Das et al. [2] and Eastman et al. [3] found that with nanoparticles suspended in fluids, the effective thermal conductivity could be increased. While much of the previous work investigating the use of nanofluids as a heat transfer fluid has focused on the single phase aspects such as thermal conductivity and convection, within the last five years groups have begun exploring the characteristics of boiling nanofluids. When considering the effect of nanofluids on the boiling traits unique aspects come to mind such as the behavior of the nanoparticles as the fluid transitions between phases.

Nanofluids are used to ensure the improvement in heat transfer and efficiency of energy in a vast variation of thermal management systems like nuclear reactors, ultrafast cooling systems, solar collectors, microelectronics, heating, ventilation and air-conditioning (HVAC) systems and automotive industries. For example, nanofluids can increase the heat transport property of lubricants and coolants in the compression ignition and spark ignition of the engines. Nanofluids with higher thermal conductivity will give us anomalous energy and cost savings. Further, nanofluids have a high potential for the systems which require lesser storage of fluids. Therefore nanofluids can make the thermal systems lighter and smaller.

II. Objectives

This work is focussed on the observation of CHF and HCT by the distilled water of pool boiling and its Alumina and MWCNT based nanofluids with surfactants SDS and Triton X-100 employed for dispersion stability. The affect of surfactants at 1% concentration is observed on dispersion stability and on the pool boiling characteristics. The transfer of heat is then observed from particle deposited SS surfaces and the resultant change in characteristic parameters is noted. Results are then relatively compared within different samples. The research is then done as follows:

- Dispersion of nanoparticles in nanofluids
- Analysis of heat transfer in boiling
- Analysis in critical heat flux (CHF)
- Comparison with effect of surfactants on
- boiling parameters.
- Effect of deposition of particle on boiling parameters

III. Experimental Methodology

A. Development of Experimental Test Ring

The setup contains boiling vessel made of borosil glass of 3l capacity for boiling the nanofluids to be tested. The container is completely insulated on the sides to maintain the bulk temperature of the liquid. Two watch areas are left open to see bubble formation and bubble growth. An auxiliary pre-heater is installed to maintain the temperature of the fluid to near saturated temperature of the base fluid at the beginning of each experiment. A condenser is installed on top of the vessel to condense the vapour produced during boiling. Two test heaters, SS wire (0.4mm diameter, 100mm length), and SS heater cartridge (10mm diameter, 100mm length) are tested individually for HTC and CHF analysis, respectively. The cartridge heaters are fitted with four k-type thermocouples, installed on the surface of heaters. The bulk temperature of the nanofluid is also measured using another k type digital thermometer. An AC variable power supply is used to power the test heater. The power supply is observed using watt meter. A camera working at 100fps is installed on side of the apparatus to see bubble formation and bubble growth at variable power supplied. A digital microscope is installed to observe deposition of particle and scaling because of the nanofluid pool boiling. The experiments are all done under the atmospheric pressure.

B. Nanofluid Preparation

Al2O3 and MWCNT are separately used at variable concentrations under presence of SDS and Triton X-100 surfactants, individually; they are fundamentally dispersed in deionised water as base fluid. Nanoparticle and base fluid solution is first mixed using magnetic stirrer at 700 rpm for 1 hour, for complete dispersion at a macroscopic level. The solution is then exposed ultra-sonication process for 6 hours each time, to homogenously disperse the nanoparticle within the base fluid. Similarly, surfactants SDS 1wt% and Triton X-100 1vol% were used for additional dispersion stability, individually. Used surfactants were homogeneously mixed using magnetic stirrer until a clear surfactant solution is obtained. The stirring is again done after mixing nanoparticles. The process is then again followed by ultra-sonication. In the above processes nanoparticles are added at concentrations of 0.01wt% 0.05wt% and 0.1wt%.

In these two processes it was seen that nanofluids stabilised via. surfactants as surfactants showed stability for a longer time. Nanofluids stabilised without surfactant solutions were found stable for 2-3 days, whereas those with surfactants were found stable for over a week.

No sign of nanoparticle agglomeration or deposition was seen during the pool boiling experiment. Since the amount of Triton X-100 and SDS was very small, the saturation temperature of water + surfactant solutions wouldn't differ from pure water.

The nanoparticles were supplied from Ad-Nanotech Pvt. Ltd., India and surfactants were supplied from Loba Chemie Pvt. Ltd., India. The technical parameters describing two physical properties of the nanoparticles are described in the given tables.

IV. WORKING METHODOLOGY

Before each experiments, the boiling vessel, test heater and auxiliary heaters are thoroughly cleaned using toluene and distilled water so that any unwanted particles are absent from both the surfaces. Fluid is then heated to near saturation temperature using auxiliary heaters. Watt meter is then switched on to measure the supplied power to the heaters. The water supply is turned on to the condenser to condense the vapours generated due to boiling. The images are taken using a camera at 100fps to see the bubble formation and bubble growth. The test pieces are then examined under the digital microscope to observe scaling and deposition of particle on a micro level. During test no boiling hysteresis was observed indicating least dissolved gas.

For CHF measurements, the SS wire is installed between the electrodes and immersed into the nanofluid. The power is then supplied and boiling starts off the surface. As the power supplied approaches to the critical heat flux vigorous bubble formation and noise off the wire is observed and eventually wire breaks indicating burnout failure. Same procedure is done for each nanofluid combination. To observe the effect of deposition of particles by nanofluid on the CHF in the presence of water, the power is supplied at fixed interval up to CHF (critical heat flux) so that particle deposition occurs, the power is then switched off and wire heater is then replaced in deionised water instantaneously. The power is then again increased at regular intervals up to critical heat flux so that burnout failure occurs. The difference in heat fluxes is measured for each such run.

For HTC measurements, the SS heater cartridge is installed vertically aligned in the fluid. The power is then supplied starting at 30kW/m^2 (approx.) and increased at fixed intervals of 15kW/m^2 (approx.) up to the maximum of 475kW/m^2. Each increment is done at the interval of two minutes to as to maintain thermal equilibrium at the heater surface. The bulk temperature of fluid and surface temperatures are taken by thermocouples at each interval.

A. Data Reduction and Uncertainty Analysis

Presently, critical heat flux (CHF) and heat transfer coefficient (HTC) are obtained via calculations from the following set of equations:

The resultant input power to the heater, Qin, is calculated as:

$$Q_{in} = VI$$

Where, V and I are the voltage and current supplied, respectively. Qin is the resultant input power Heat flux can then be obtained by the following equation:

$$Q''_{in} = \frac{Q_{in}}{A}$$

Where, A is the surface area of the heater, q'' is the supplied heat flux Similarly, for critical heat flux (CHF)

$$Q''_{in(CHF)} = \frac{Q_{in(max.)}}{A}$$

Similarily, the pool boiling heat transfer coefficient (HTC) can be calculated as:

$$\Delta T_{Sat.} = T_{surface} - T_{sat}$$

$$h = \frac{Q''_{in}}{\Delta T_{Sat.}}$$

Where, Tsurface is the heater surface temperature, Tsat is the saturation temperature of the fluid, ΔTsat is the wall superheat, h is the pool boiling HTC.

Since the experiments are single sample in nature, individually; the uncertainty is measured using Kline and McClintock method [27].

$$\pm F = \left[\left(\frac{dF}{dx_1}\right)^2 (\varepsilon_1)^2 + \left(\frac{dF}{dx_2}\right)^2 (\varepsilon_2)^2\right]^{1/2}$$

Where, x_n are the measurements made, ε_n is the tolerance is parameters and F is the function used.

The uncertainties in different parameters are as:

V. PARAMETRIC ANALYSIS

In these experiments, the obtained data via pool boiling of distilled water is compared against the Rohsenow's correlation [75] in order to check the accuracy of these work, Fig. 3. The data is then be taken as reference to compare the results obtained from nanofluid samples. Rohsenow's Correlation:

$$h = \frac{1}{C_{sf}}\left[\frac{C_{pf}q''}{h_{fg}}\right]\left[\frac{q''}{\mu_f h_{fg}}\left(\frac{\sigma}{g(\rho_f - \rho_g)}\right)^{1/2}\right]^{-1/3} Pr^{-n}$$

The data obtained for the present case of SS surface and distilled water, gives the value of Csf and n as 0.008 and 1.0. The HTCs thus obtained limit within 5% deviation off the predicted data.

Similarly, for CHFs, the comparison is made against Zuber correlation, eq. (2), which predicts the value to be 110W/cm^2

$$q''_{CHF} = 0.131 h_{fg} \rho_g^{1/2} \left[g\sigma(\rho_f - \rho_g) \right]^{1/4}$$

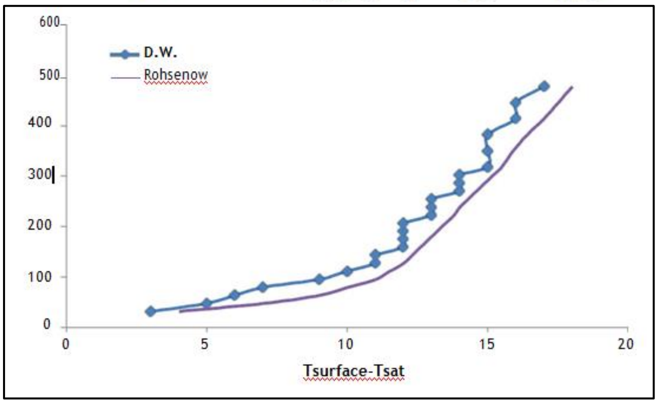


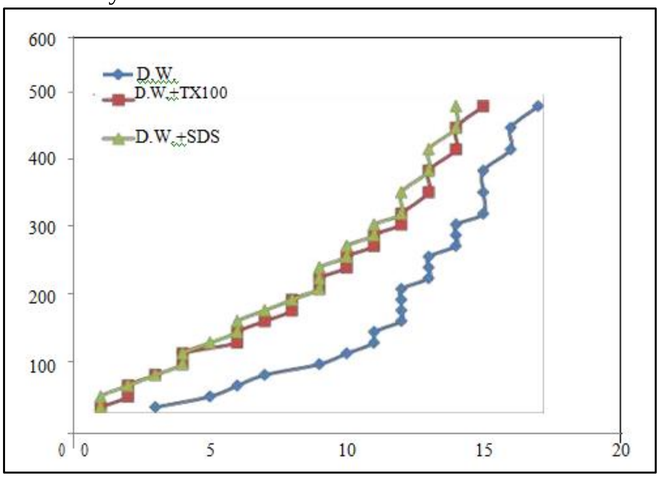
Fig. 1: Validation of boiling curve for water against Rohsenow's correlation

Kruse et al. also made a similar comparison, and found it to be in an agreement with Zuber's correlation. The measured data with distilled water, thus in good comparison with other researcher's data and thus confirms the accuracy of the apparatus and the method.

A. Parametric Study

1) Heat Transfer Coefficient (HTC)

Fig.2 shows pool boiling curves for distilled water and its solution of 1wt% SDS and 1vol% of 95% solution of Triton X-100. The pool boiling curve for the solutions of surfactant is seen to be shifted left, thus indicating heat transfer increment. Same results were obtained by Wen and Wang, Although at 1% concentration, the pool boiling curves of both surfactant solutions are observed to follow similar trends. Heat transfer enhancements ranging from 20% to 70% are seen for the set of solutions within the range of heat fluxes. The increment in HTCs is reasoned by increased wettability of surfaces indicating less reduction in nucleation site density.



Tsurface-Tsat [°C]

Fig. 2: Boiling curves for water and its surfactant solutions

Fig. 3 and Fig. 4 show the boiling curves for MWCNT-Water and Al2O3-Water nanofluids of different concentrations and surfactants. It is observed that the pool boiling of HTCs increase with enhanced heat flux for both nanofluids, similar to water. However, it is seen that the boiling curves for nanofluids shifts towards right of the boiling curve of water, indicating higher superheat at similar heat transfer and heat fluxes deterioration. Since, thermal conductivity of MWCNTs is so much larger; the thermal conductivity of its nanofluid also increases, thus it is expected that boiling HTC of nanofluids should be higher than water. But, characteristic behaviour of pool boiling of nanofluids depends on many other factors like property of base fluid, nanoparticle concentration, surface morphology, dispersion stability and surfactants used.

A noticeable deterioration in the HTCs is observed above heat flux of 200W/m^2. The deterioration is seen to be increasing with increased nanoparticle concentration. This is an attributed to the deposition of the nanoparticles on heater surfaces via microlayer evaporation which clogs the nucleation sites and eventually prevents bubble formation and reducing HTCs. It is also seen that MWCNTs provide higher deterioration than alumina. This may be reasoned to the structural differences of nanoparticles used; although, further experiments are needed.

Also, while deterioration is thoroughly obtained for all range for nanofluids, an enhancement is obtained for nanofluids with surfactants at same nanoparticle concentrations. It is observed that both Triton X-100 and SDS; at a low concentration of 1%, provide similar enhancements in HTCs. Note that this enhancement is only compared to that of nanofluids without surfactants at same concentration; as compared to distilled water, there is still deterioration. This is credited to the increased wettability and lower deposition observed on the heater surfaces. The same leads to excessive bubble formation, which in turn enhances the HTCs for the nanofluid with surfactants.

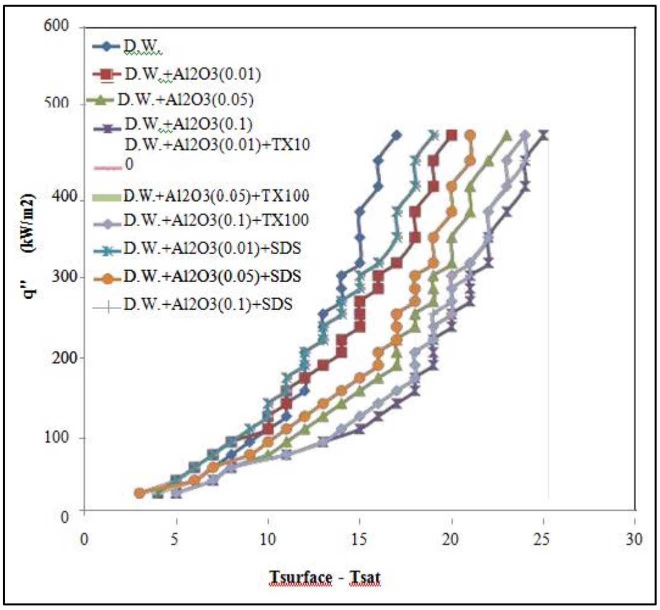


Fig. 3: Boiling curves for Al2O3 nanofluids

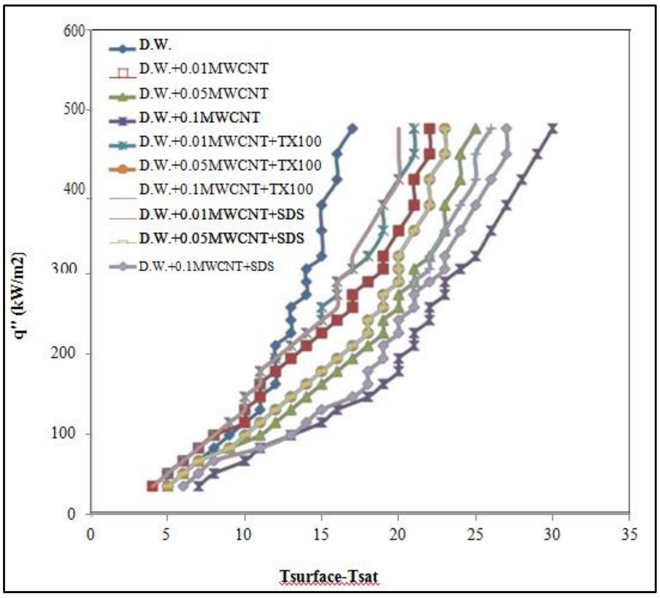
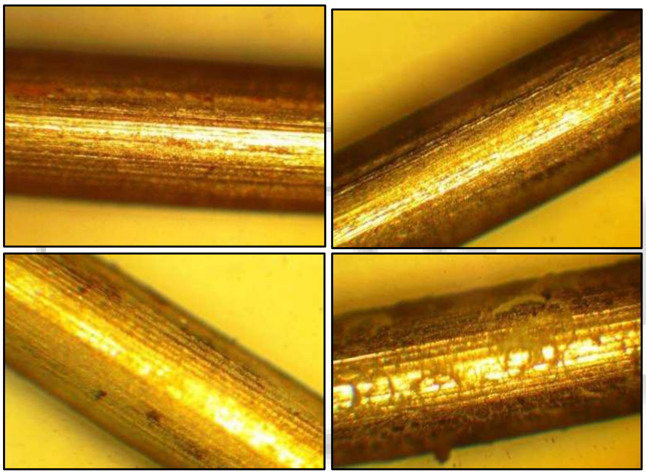


Fig. 4: Boiling curves for MWCNT nanofluids

B. *Particle Deposition*



VI. CONCLUSION

Presently, pool boiling HTCs and CHFs are measured via SS wire heater and cartridge heater surfaces immersed in liquid at near saturation temperature. MWCNT and alumina nanofluids are used with particles dispersed weight concentrations of 0.01%, 0.05%, 0.1%. To confirm dispersion and to observe effect of surfactants, SDS and Triton X-100 dispersants are used. From the set of experiments performed, following conclusions can be drawn:

1) Nanofluids enhance the critical heat flux for the pool boiling case irrespective of the used particle and the dispersion practice employed. Even at lower concentrations of 0.01%, MWCNT-Water based nanofluids provided a maximum enhancement of 155%. CHF enhancement is also observed to be increasing with decrease in nanoparticle concentration. It is noted that surfactant based nanofluids give lower CHF enhancement while compared with pure water based nanofluids. Overall the critical hat flux enhancement lies within the range of 50% - 150%.
2) In this case HTC deterioration is seen for all the range of nanofluids when compared with the pure water. HTC deterioration is seen within the range of 20%-50%. Although when surfactants are used, a slight increment in heat transfer coefficient is noted because of surface wettability enhancement by deposition of particle and physical change in properties of liquid.

The deposition of particle images show deposition with different concentrations for different nanoparticles. The deposition is found to be stable even in the presence of new liquid environment, suggesting the presence of an adhesive force binding the particle to the surface. Change of surface morphology also verifies with the active nucleation site, enhanced heat transfer and surface wettability, thus decreasing the heat transfer coefficient and enhancing critical heat flux.

VII. APPLICATIONS & FUTURE SCOPE

A. *Applications*

Nanofluids pool boiling has well established its position in the field of high heat transfer applications. In automotive industries lighter and smaller heat transfer equipments are always required improve fuel efficiency with reliability of automotive parts. In microelectromechanical systems (MEMS) where compact space and longevity of product is in upmost demand, increased heat transfer by nanofluids fulfils them adequately. Nanofluids also find application in heavy drilling projects and in electrical transformers.
To sum it up nanofluids find their use in these specific areas:

– Electronic Cooling
– Refrigeration and Air conditioning
– Automotive Industries
– Nuclear, Solar and Thermal Power Plants
– Chemical and Bio-Medical Industries.
– Heavy Electrical Industries

VIII. FUTURE SCOPE

Future research needs to focus on finding out the main parameters affecting the heat transfer rates and max heat flux of different nanofluids. The in depth study of particle deposition, time deposition rates, surface characteristics need to be done on the macroscopic level. On the microscopic level, the effect of particle size, particle shape, and thermos-physical properties of individual nanoparticles need characterisation and study. The effect of dispersion stability and dispersants on thermal properties also needs to be taken care of. Finally, and of utmost importance is the development of the theoretical model for the mathematical explanations of the behaviour of nanofluids, to generalise their nature in heat transfer.

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