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Enhancement of Pool Boiling Performance using SWCNT based Nanofluids: A Sustainable Method for the Wastewater Heat Recovery

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***Abstract:* Heat extraction from wastewater is an important and challenging task in the industry. Performance of the heat extraction decreases mainly due to the boiling crisis. Researchers are using nanofluids as a better alternative for conventional base fluids. Nanofluids exhibit better performance due to higher thermo-physical properties. Thus, in this study, we used single-walled carbon nanotubes (SWCNT) for the boiling operation. In the experimentations, we used two types of heater surfaces; the first is bare heater surface, and the other is the SWCNT deposited heater surface. Then we compared the performance of both heater surfaces. The critical heat flux (CHF) value observed in the case of nanoparticle deposited surface is 2.14 MW/m^2 and the CHF value observed in bare heater surface is 2.26 MW/m^2. This observed increment in nanoparticle deposited surface promotes the smaller size of the bubbles at a rapid rate and reduction in bubble size occurs because of the increased surface roughness. The heat-transfer coefficient is also 5 % more in the nanoparticle deposited surfaces than the bare heater surface.**

***Keywords*: Waste heat recovery, SWCNT, Critical heat flux, Nanofluids, Nanoparticle deposition.**

Nomenclature and Abbreviations:

CHF	Critical Heat Flux
MWCNT	Multi-walled Carbon Nanotubes
HTC	Heat Transfer Co-efficient
AWG	American wire Gauge
NiCr	Nichrome (an alloy of 80% nickel and 20% chromium)
d	Diameter of wire
L	Length of wire
V	Applied Voltage
I	Current
q_{CHF}	Critical heat flux (kWm^{-2})
FTIR	Fourier Transform Infrared Spectroscopy
SEM	Scanning Electron microscopy
DSC	Differential scanning calorimeter
d_{bf}	Base fluid equivalent diameter
ρ_{nf}	The density of the nanofluid
ρ_{np}	The density of the nanoparticle
ρ_{bf}	The density of the base fluid
Φ_{np}	The volume fraction of the nanoparticle
C_{pnf}	Specific heat value of the nanofluid
$C_{p,np}$	Specific heat value of the nanoparticle
C_{bf}	Specific heat value of base fluid
k_{nf}	Thermal conductivity value of the nanofluid
k_{np}	Thermal conductivity value of nanoparticle
k_{bf}	Thermal conductivity value of base fluid
μ_{nf}	Nanofluid viscosity
μ_{bf}	Base fluid viscosity
d_{np}	Nanoparticle diameter
N	Avogadro number
M	Base fluid molecular weight
h_{fg}	the heat of vaporization (kJ/kg)
σ	Surface tension value between air and water (N/m)

I. INTRODUCTION

Heat loss with wastewater is an important challenge for the wastewater industry. This heat is generally recovered by using heat recovery boilers. Pool Boiling is a physical phenomenon that is associated with the change in phase from liquid to vapor. [1-8] During this phenomenon the buoyancy effect of the vapor produced due to the concentration difference brings the boiling effect into action. During boiling vapors are produced from the liquid in the form of 'nucleate' bubbles. Boiling heat transfer is one of the most important processes involved in industries. A lot of liquids also undergo boiling while cooling of other exothermal processes. The liquids which are used to absorb heat evolved from other processes are regarded as coolants. [9-18] Coolants are generally expected to have high thermal conductivity and rate of heat flux while maintaining low-cost and chemical neutrality to surface materials since their application in cooling processes. Sometimes during cooling application, a vapors blanket forms around the heating surface resulting in localized heating, which causes the meltdown of the heated surface [19-34] and hence damage to equipment and/or serious safety hazards. The point at which this phenomenon occurs is termed critical heat flux (CHF). [35-52]

Nanofluids have been observed to enhance the CHF point of the fluids which results in the prevention of the heated surface meltdown. [53-62] Nanofluids have been used for heat transfer applications since they have superior heat transfer qualities to their conventional counterparts. Several studies have been undertaken to observe different characteristics of nanofluids under different circumstances, such as different particle sizes, different volume concentrations, different types of base fluids, different types of nanoparticles, etc. and a lot of different mechanisms have been contemplated for the enhancement of their heat transfer characteristics such as surface wettability, wick ability, surface roughness, Brownian motion, etc. [63-74] In such a study Kumar et al. [75-78] used three different types of nanofluids, namely Al2O3, Fe2O3 & CuO at different volume concentrations and found their CHF enhancements to be 130, 122 & 51% at 0.03, 0.05 & 0.05% vol. % respectively. They attributed the higher enhancement in the case of alumina nanofluids at a smaller volume concentration due to the smaller particle size of alumina nanoparticles which might be a cause of the prevention of agglomeration of nanoparticles. In a different study Song et al. [79-86] used two different test sections of two different sizes both being made of stainless steel then submerged the test sections consecutively inside the nanofluid pool with electrodes attached to them to find out the CHF of the nanofluids. They used SiC nanofluid with particle volume concentrations of 0.0001, 0.001 & 0.01 % and found out the enhancements to be 39.6%, 36% & 53.5% and 36.2%, 0%& 105% for 1 by 5 and 5 by 5 test sections respectively. They regarded the enhancement due to the deposition of nanoparticles on the test surface and confirmed it by imaging the test sections under SEM. For 0.001% volume concentration in 5 by 5 test section cases, the CHF enhancement effect due to nanoparticle deposition was compensated by wettability change to hydrophobicity and hence the drop in CHF enhancement was seen.

II. MATERIALS AND METHODS

Experimental Work

We used sodium oleate as a surfactant for the stability of the nanofluid. Sodium oleate is comparatively cheaper than the other surfactant available, and it is good on a broad temperature range. Enhancement in the critical heat flux is explained by using the bubble dynamics data. Bubbles are captured by using the high-speed resolution camera. The diameter and other parameters are calculated by using the ImageJ software. These bubble dynamics data are useful to explain the enhancement in the critical heat flux and heat transfer co-efficient.

Preparation of the nanofluids and deposition of the nanoparticles on the heater surface

Firstly, SWCNT is taken in a suitable amount and added to the water. This mixture is sonicated for 2 hours by using the Probe type sonicator. Sonicator used to remove the surface charges of the SWCNT nanoparticles. Due to the removal of the surface charges, the stability of nanofluid increases. A significant amount of sodium oleate is added to nullify the remaining surface charges. In each experimentation, a surfactant of 25 wt % of SWCNT quantity is added. The concentration of SWCNT is varied from 0.001 to 0.01 vol% for each experimentation. Nanoparticles above this concentration start to agglomerate and thus, the performance of nanofluid decreases.[27-29] The stability of SWCNT is checked by dynamic light scattering equipment (Zeta-Sizer Make: Malvern Panalytical) and results are tabulated in Table 1. These nanofluids are allowed to deposit the nanoparticles on the heater surface by performing the experimentation at the saturation temperature of 5^0C and volume concentration of 0.005 vol%.

Experimental Setup

A schematic representation of the critical heat flux apparatus is given in Figure 1A and real-time photograph of the apparatus is shown in figure 1B. Glass chamber is used to run the experiment. In the glass chamber, approximately 5 liters of nanofluid is collected and two electrodes are used to short the nichrome wire. This short ire can also be called a test material or heater material. Nanofluid is preheated before running the boiling experiment. The temperature of the nanofluid is kelp 10-20^0C less than the saturation temperature. After this, boiling experimentation starts. The secondary heater is allowed to heat the nanofluids. The heat flux of the nanofluid is regulated by using the dimmerstat. Thermo-couples are added to monitor the temperature throughout the experimentation. 6 cm long and 0.27 mm diameter NiCr wire (32 AWG) is used as a secondary heater. All the experimentations are conducted at the atmospheric conditions.

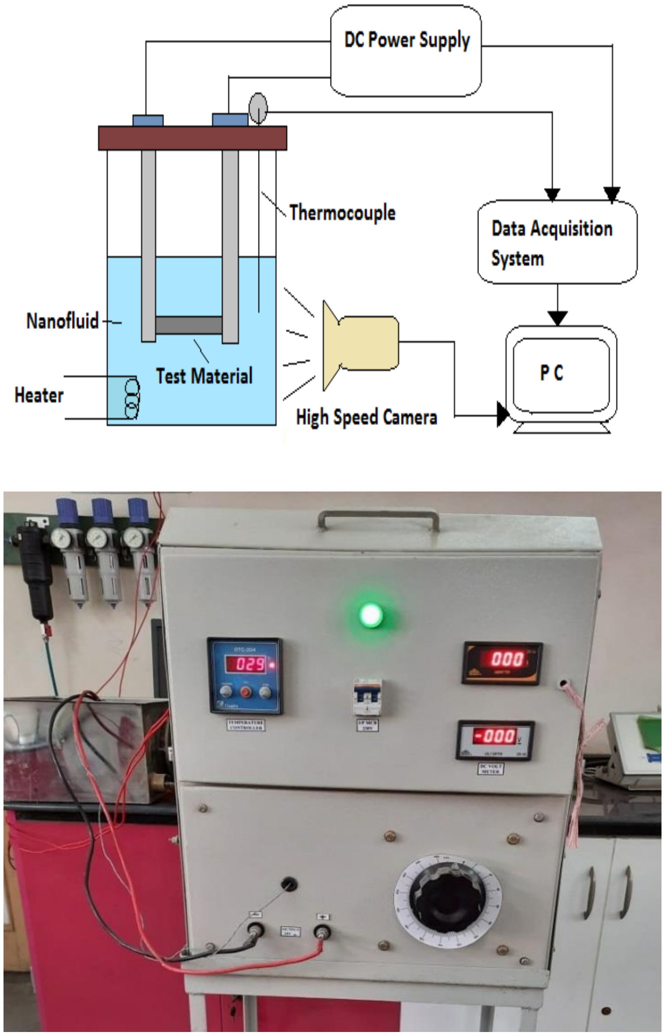

Figure 1: CHF measuring Instrument (A)Schematic diagram of instrument set-up; (B) Real-time image of the instrument

Figure 2: Real-time images of bubble formation

Measurement of Critical Heat Flux

First of all, nanofluid is added to the glass chamber. Then it is allowed to heat up to 10-20 °C less than the saturation temperature. Then heating by the pre-heater is stopped and nichrome wire is allowed to heat. Heat flux is regulated by using the dimmerstat. The critical heat flux value can be noted as a sudden drop in the current after increasing the voltage or the breaking of the nichrome wire due to the bubble cloud near the heater surface. Then, the critical heat flux value can be calculated by using equation (1). [30].

$$q_{CHF} = \frac{VI}{\pi d L} \qquad \text{……… (1)}$$

Zuber's co-relation is also useful for the theoretical critical heat flux calculation. This equation is primarily valid for low-pressure liquids. Zuber's equation is represented by equation (2). [31-33]

$$q_{CHF} = C h_{fg} \rho_v \left(\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right)^{0.25} \qquad \text{……… (2)}$$

ρv, ρr are the respective densities of vapor and liquid (kg/m^3) and the value of the constant C is π/24.

The heat transfer coefficient (HTC) can be calculated using equation 3:

$$h = \frac{Q}{A(T_w - T_b)} \qquad \text{……… (3)}$$

Characterization and Data Reduction

Characteristics of SW-CNT

SWCNT is purchased from sigma Aldrich for the synthesis of the nanofluids and used without further modification. Water is taken as a base fluid. Figure 3 shows the DLS results of the pristine SWCNTs, from this result we can conclude that the size of the SWCNT is 39.41 nm.

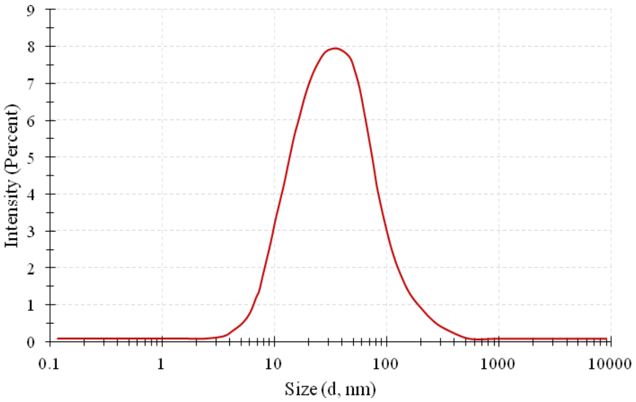

Figure 3: DLS result of pristine Single-walled carbon nanotubes

Thermo-physical properties of the nanofluids

Thermo-physical properties are mainly influenced by the stability of nanofluids.[34-36] Stability of nanofluids can be measured by the zeta potential value of the nanofluids. The dynamic light scattering technique is mainly used to measure the zeta potential value. Nanofluids with the zeta potential value in the range of +30 mV and -30mV are considered less stable nanofluids. Nanofluids with value other than these values are considered stable nanofluids.[37-39] Zeta potential values of the nanofluids are tabulated in Table 2. The stability of the nanofluids is best at the value of 0.005 vol% of the SWCNT. Then further addition of nanoparticle concentration decreases the stability of nanofluids. This is the decrease in the stability of nanofluids can be justified by the agglomeration of the nanoparticles at the higher concentration.

TABLE 2
Zeta potential of the nanofluids concerning the nanoparticle concentrations

The concentration of SWCNT (Vol%)	Zeta Potential value (mV)
0.001	+31.07
0.003	+33.08
0.005	+35.52
0.007	+32.14
0.01	+31.47

Thermo-physical properties are useful for heat transfer enhancement. Temperature and concentration of nanoparticles are the main factors for the thermophysical properties. Specific heat and thermal conductivity are considered thermal properties. Density and viscosity are considered physical properties. KD2 pro thermal properties analyzer is used to measure the thermal conductivity of the nanofluids. (MAKE: Decagon Devices Inc, USA) density is measured by the electronic weighing machine. Viscosity is measured by the Capillary viscometer and a differential scanning calorimeter is used to measure the specific heat of the nanofluids.

Equation (4) is used to calculate the theoretical value of density. [40]

$$\rho_{nf} = \rho_{np}\Phi_{np} + \rho_{bf}(1 - \Phi_{np}) \qquad \text{…. (4)}$$

Equation (5) is used to calculate the specific heat [41]

$$C_{pnf} = \frac{C_{p,np}\rho_{np}\Phi_{np} + \rho_{bf}C_{bf}(1 - \Phi_{np})}{\rho_{nf}} \qquad \text{….(5)}$$

Equation (6) is used to calculate the thermal conductivity of the nanofluids. [42]

$$k_{nf} = \frac{[(k]_{np}\Phi_{np}) + 2k_{bf} + 2(k_{np}\Phi_{np} - k_{bf}\Phi)}{[(k]_{np}\Phi_{np}) + 2k_{bf} - (k_{np}\Phi_{np} - k_{bf}\Phi)} k_{bf} \qquad \text{……(6)}$$

Equation (7) is used to calculate the viscosity of the nanofluids [43]

$$\mu_{nf} = \frac{\mu_{bf}}{1 - 34.87\left(\frac{d_{np}}{d_{bf}}\right)^{-0.3} \Phi^{1.03}} \quad when\ \Phi \le 10\ \% \qquad \text{….. (7)}$$

d_{bf} is calculated by the equation (8)

$$d_{bf} = 0.1 + \left(\frac{6M}{\pi N \rho_{bf}}\right)^{0.3} \qquad \text{……(8)}$$

Calculated and experimentally determined thermo-physical properties are compared in figure 4.

Uncertainty analysis

Analysis of uncertainty during the experimentation is important for a better understanding of the performance of the system. Uncertainty in output results arises due to the experimental and calculation errors. Key parameters contributing to the uncertainty during the calculation and experimentation are tabulated in Table 3. The most useful method for error calculation is the root mean square method. The root mean square method is represented by equation 10. [44-46]

$$\Delta R = \left[\left(\frac{\partial R}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\Delta x_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\Delta x_n\right)^2\right]^{1/2} \qquad \text{...(10)}$$

x_1 and x_2 are the respective parameters contributing to the error.

For example, Equation (5) can be used to calculate the heat transfer rate.

$$\partial Q = \left[\left(\frac{\partial Q}{\partial m}\Delta m\right)^2 + \left(\frac{\partial R}{\partial Cp}\Delta Cp\right)^2 + \left(\frac{\partial Q}{\partial Tout}\Delta Tout\right)^2 + \left(\frac{\partial R}{\partial Tin}\Delta Tin\right)^2\right]^{1/2} \qquad \text{….(11)}$$

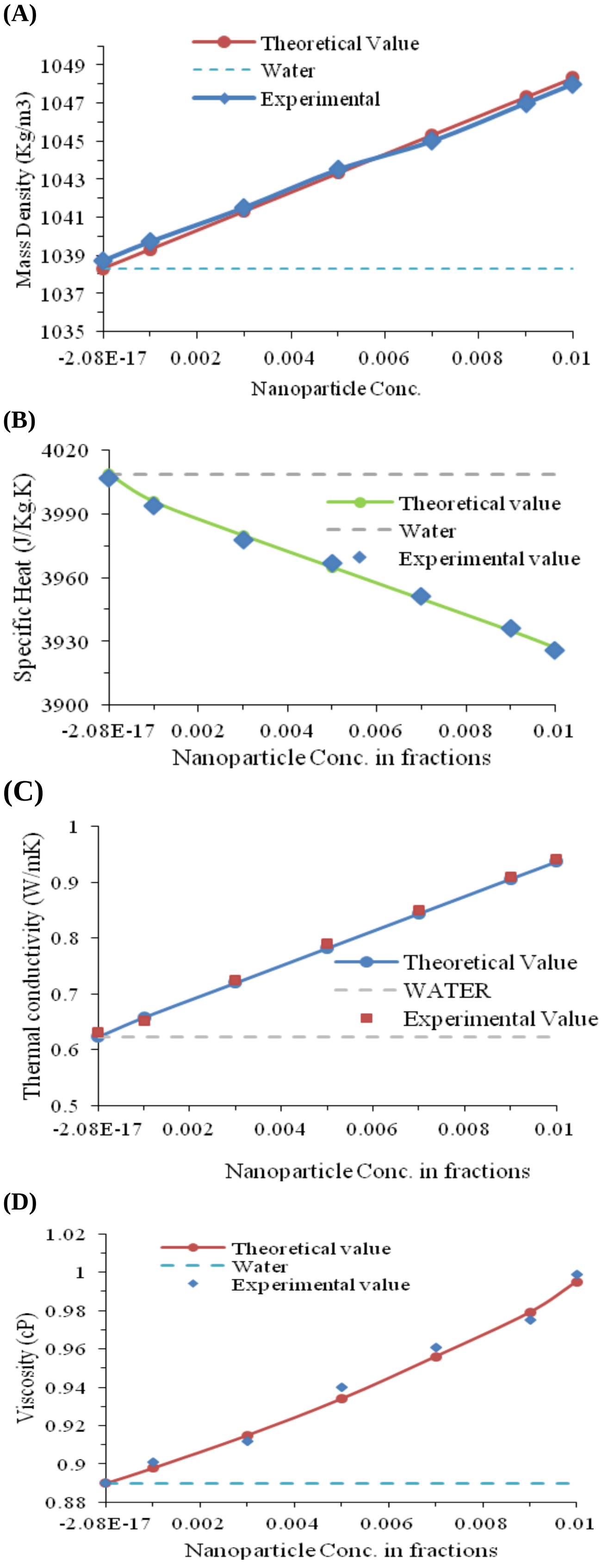

Figure 4: Comparison of Theoretical and Calculated thermo-physical properties of nanofluids (A) density (B)Specific heat (C) Thermal Conductivity (D) Viscosity

TABLE 3
Uncertainty analysis of the parameters and instruments

Parameter	Uncertainty
Heater Temperature	±0.1
Voltmeter	±0.5
Bubble diameter	±5.0
Ammeter	±0.5
Temperature sensor	±0.5
Critical heat flux	±0.5
Boiling Heat Transfer Co-efficient	±0.5
Wait, growth and recycle time	±2.5
Bubble departure frequency	±2.5

III. RESULTS AND DISCUSSION

Comparison of pool boiling performance for SWCNT-water nanofluid on a bare heater surface and SWCNT deposited surface

Performance of the pool boiling curves for the SWCNT-water nanofluids on the bare heater surface and SWCNT deposited surface is represented in Figure 4 A. Critical heat flux value comparison of both systems is represented in figure 4 B. various co-relations like zubers co-relation are used to calculate the critical heat flux of nanofluids.

In the experimentation, we found that the critical flux value for the water as a working fluid is 1.327 MWm^{-2}. While from the zubers co-relation, the calculated value of critical heat flux is 1.36. This uncertainty in the value is due to the experimental and calculation errors. The values are compared for the nanoparticle concentration of the 0.003 vol%, 0.005vol% and 0.007 vol%. The best results obtained for the bare heater surface are at 0.005vol% of the nanoparticle concentration. Critical heat flux enhancement is recorded at the 2.14 MWm^{-2} while; in the case of the nanoparticle deposited surface, critical heat flux enhancement is 2.26 MWm^{-2}. The critical heat flux value starts to decrease after this, because of the accumulation of nanoparticles. From the comparison of both surfaces, it is clear that the deposition of the nanoparticles on the surface allows the roughness on the heater surface. This roughness decreases the contact angle and thus, leads to an increase in the surface wettability.

The boiling heat transfer of the nanofluids is greatly dependent on the bubble dynamics of the vapors leaving the heater surface. The fluid in immediate contact with the heater surface receives the energy and this allows the formation of the bubbles. This bubble separates from the heater surface and transfers the energy to the bulk of the working fluid. This transfer of energy occurs after the collapse of the bubble. The continuous collapse of the bubbles allows for more heat transfer co-efficient. [47-49]

Figure 5 illustrates the change of the heat transfer coefficient over the different nanoparticles concentration for both the cases of the heater. This constant is also called Newton's cooling law constant. The deposition of the nanoparticle is the main reason for the enhancement of critical heat flux.

Deposited nanoparticles are the reason behind the increment of the critical heat flux. These deposited nanoparticles have better thermo-physical properties than the working fluid. This helps in the increment of the heat transfer coefficient. From figure 5, it is clear that the nanoparticle deposited surface exhibits a better performance of the boiling than the bare heating surface. Comparatively, 5% more enhancements in the heat transfer coefficient are observed in the nanoparticle deposited surface than the bare heater surface at the 0.005 vol% of nanoparticle concentration.

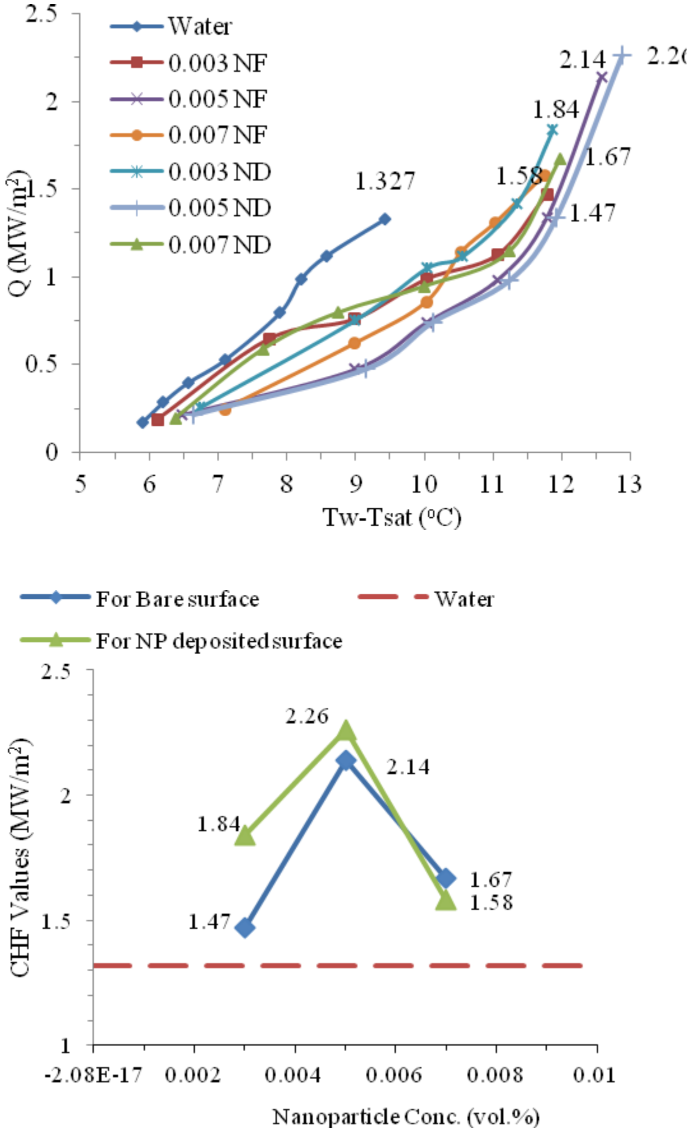

Figure 5: (A) Boiling curve for MW-CNT -water Nanofluid for the bare heating surface and nanoparticle deposited surface (B) CHF data for MW-CNT -water Nanofluid for the bare heating surface and nanoparticle deposited surface

Comparison of the Boiling Heat transfer coefficient (HTC) for the nanoparticles deposited surface and bare heating surface

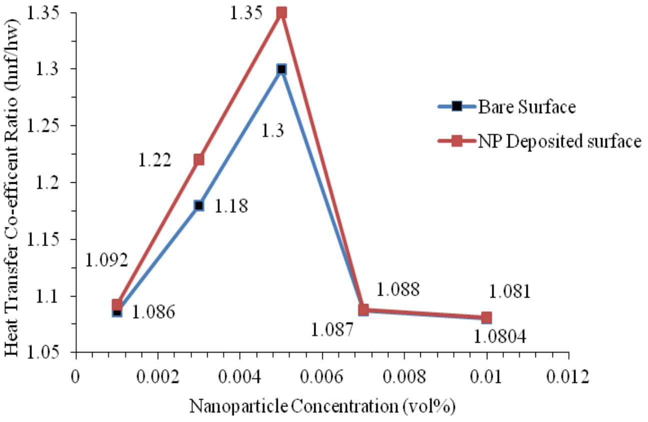

Figure 6: Boiling heat transfer Co-efficient of the SWCNT/water-based nanofluids at the various nanoparticles concentrations

Comparative bubble dynamics

A high-resolution camera is used to capture the image of the bubbles leaving from the heating surface. ImageJ software is used to calculate the bubble diameter. These bubble dynamics are the main reason for the increase in the critical heat flux value. Each experimentation is repeated 6 times and values are averaged for all the experiments. In this experimentation, we have calculated the bubble diameter, bubble growth time, bubble wait time and bubble departure frequency. Bubble diameter is studied by using the ImageJ software. [50-51]

Bubble departure diameter: Figure 6 represents the comparison of the bubble departure diameter for the two superheat temperature values of 5 °C and 10 °C. An increase in the nanoparticle concentration in nanofluids decreases the bubble diameter. Because an increase in the nanoparticle concentration leads to an increase in surface roughness. Increased surface roughness decreases the bubble diameter. From these results, it is clear that the porous layer of the deposited nanoparticle is responsible for the increase in the critical heat flux value and this improves the boiling efficiency. Comparatively, the nanoparticle deposited surface generates the smaller size of the bubbles than the bare heater surface. this leads to the better boiling performance of the nanoparticle deposited surface.

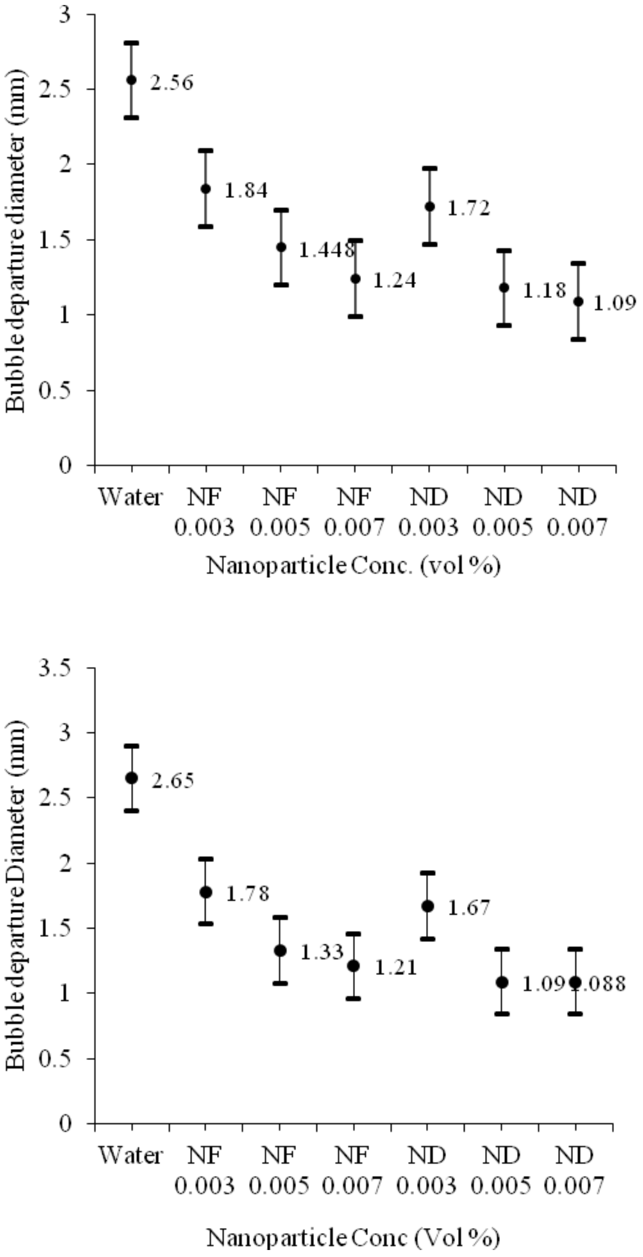

Figure 7: Bubble departure diameter at A) 105°C B) 110°C

Wait period, growth period and cycle times: Time consumed during the growth of the bubble from the heating surface is called a growth period and time consumed to start the new bubble to grow after the dissipation of the previous bubble is called a wait period. The summation of both the terms is referred to as a cycle time of the bubble. Figure 7 represents the comparative values of the wait period, bubble growth period and the cycle time of the bubble for both the heating surfaces. This figure represents the bubble dynamics at the superheat temperature of 5 °C and 10°C. The growth of the bubble is the dominating parameter in the bubble cycle of the water. But, for nanofluids, bubble growth increases very drastically and simultaneously bubble size also decreases. Nano-channels generated due to the nanoparticles deposition are important parameters of the study. These nano-channels reduce the wait time. Due to a decrease in the wait time, bubble formation is done rapidly and relatively smaller bubbles start to dissipate in the liquid bulk. Growth period less in the case of the nanoparticle deposited surface at the higher saturation temperature. This, fast dissipation of the bubbles enhances the heat transfer rates.

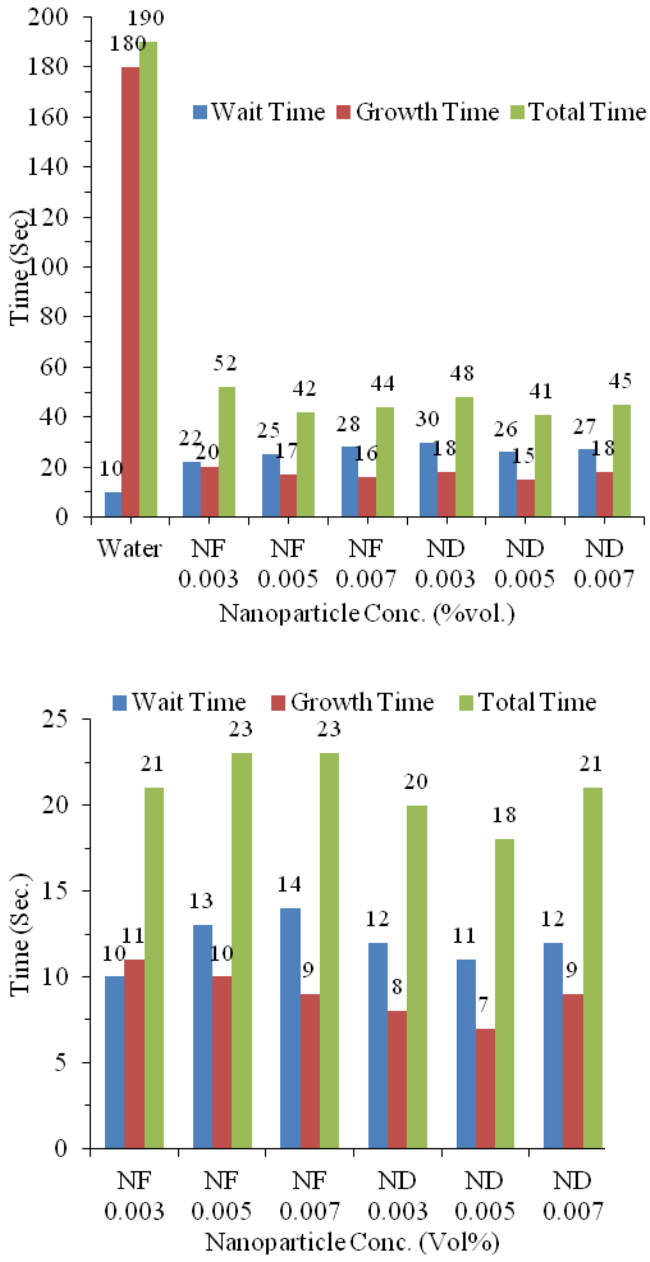

Figure 8: wait time, Growth time and Total time of bubble cycle at A) 105 °C B) 110 °C

Bubble departure frequency (*f*): Equation (12) is useful to calculate the bubble departure frequency. This parameter is useful to give the dissipation rate of the bubbles from the heater surface. Bubble departure frequency is the rate at which the bubble cycle completes per unit time.

$$f = \frac{1}{t_w + t_g} \qquad \text{.......(12)}$$

Figure 9 illustrates the bubble frequency for both the surfaces at various nanoparticle concentrations. at 105^oC and 110 ^oC. From figure 8, it is evident that the bubble departure frequency increases with the deposition of the nanoparticles. These deposited nanoparticles allow the formation of the nano-channels on the heater surface. Thus, the smaller size of the bubbles is formed. This deposition also makes sure to limit the growth period of the bubbles. due to an increase in the saturation temperature, the bubble departure frequency also increases.

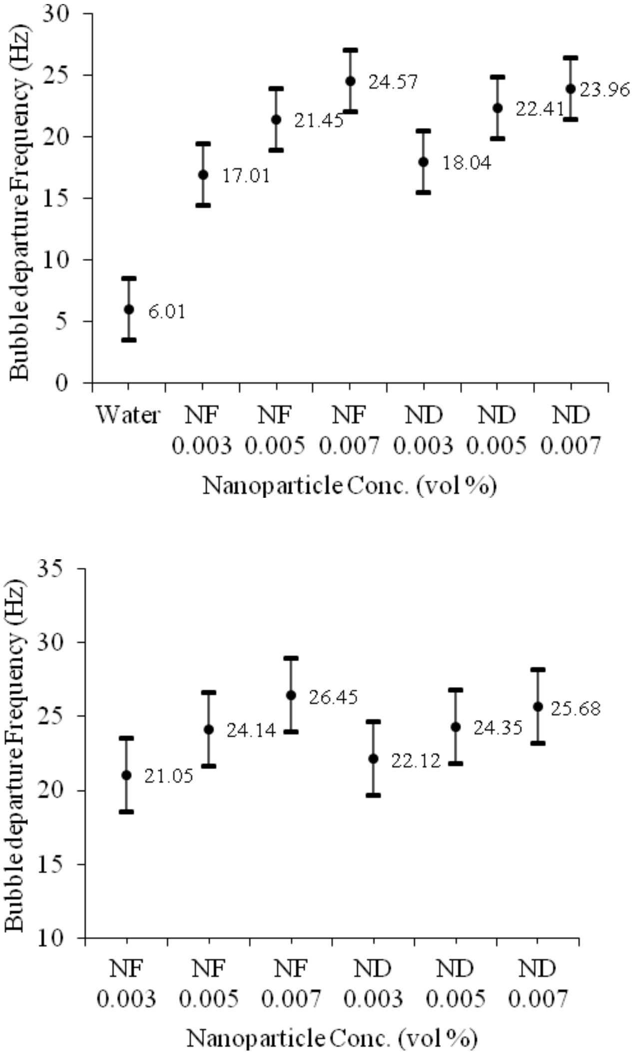

Figure 9: Bubble departure frequency at A) 105 ^oC B) 110 ^oC

IV. CONCLUSION

In this paper, we have compared the performance of the bare heater surface, and nanoparticle deposited surface in the pool boiling operation. Pool boiling is important for the energy sustainability of the wastewater heat recovery and incinerator heat recovery process. In this paper, we observed that the increase in the nanoparticle concentration results in the increase of critical heat flux. We also observed that, the nanoparticles deposited surface has a better performance compared to the bare heater surface. This is due to the deposition of the nanoparticles on the heater surface and deposited nanoparticles create nano-channels on the heater surface. These nano-channels promote the surface roughness and thus, the contact angle is also decreased. This decreased contact angle allows dissipating the bubbles rapidly; this results in a higher boiling performance. The critical heat flux observed in the case of the bare heater surface is 2.14 MW/m^2 and in the case of the nanoparticle deposited surface, the critical heat flux is 2.26 MW/m^2. The heat-transfer coefficient is also 5 % more in the nanoparticle deposited surfaces than the bare heater surface.

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