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Augmentation of Pool Boiling Heat Transfer Using Graphene-MWCNT/Distilled Water Hybrid Nanofluids

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Abstract

The pool boiling of Hybrid Nanofluids consisting of Graphene-MWCNT/ distilled water over a heated Nichrome wire at different concentration of Nanoparticles has been captured using a high-speedcamera.Both the heat transfer coefficient and the critical heat flux values have been found to increase with the increase in concentration of Nanoparticles. Maximum enhancementsobtained in the critical heat flux values and thepool boiling heat transfer co-efficient were 29.11% and 71.81% respectivelyas compared to those obtained by using distilled water alone.The wiretemperature in excess (over the saturation temperature) for the nucleated boiling was found to be minimum at 0.4 % by weight of the Nanoparticles (0.1 % by volume of Nanoparticles) and a maximum decrement of 47.2% has been observed as compared to that obtained with the distilled water. The Scanning Electron Microscope (SEM) and X-Ray Diffraction(X-RD) Nanofluid characterization techniques are used to study the grain and size of nanoparticle materials. The bubble analysis is done using image analysis (image-j software) technique and bubble growth phenomena has been correlated with the boiling heat transfer characteristics

Keywords: Critical Heat Flux,Scanning Electron Microscopy(SEM),X-Ray-Diffraction(X-RD),functionalization,Graphene-MWCNT Hybrid nanofluids.

Introduction

Practical applications of boiling range from air conditioners, electronic chips to nuclear reactors. Therefore, it is important to study and investigate the fundamental parameters affecting the heat transfer process during the boiling for the safe and efficient operation of the heat exchange devices. The solid particles in the nano size have found to have higher thermal conductivity than their finite counterparts while also presenting a larger surface area. Dispersion of solid particles of sizes in the nano scale into the different fluids can significantly improve the transfer of heat within the prepared nanofluids.Carbon nanotubes (Multiwalled or single walled), Titanium dioxide (TiO_2), Copper (II) oxide (CuO), Aluminium (Al), etc. are some of the nanoparticles that have been used. The addition of nano particles besides improving the thermal conductivity,effects the contact angle and roughness of the heating surface which increases the critical heat flux value thus increasing the safety of operation with higher heat flux removal.

Different allotropes of Carbon like Diamond, Graphene and Carbon Nanotubes have found to exhibit a wide range of thermal conductivities starting from 0.2 W/mKup till ∼5000 W/mK. Multi Walled Carbon Nano Tubes (MWCNT) along with Graphene can be an excellent combination as hybrid Nanofluids are expected to exhibit a variety of thermophysical properties for thermal applications.

Synthesis of different nanoparticles to produce a hybrid nanofluid is an emerging technology in the field of Nanotechnology. The hybrid Nano fluids exhibit better thermophysical properties than that obtained using a single nanoparticle fluid and also a wide variety of desirable combination of properties for various applications. Hybrid nanofluids is found to givea betterperformancefor heat transfer applications such as in solar panels, natural convection enclosures, HVAC systemsetcbutgive a higher pressure drop due to increased viscosity. Most of the research carried out on the hybrid nanofluids have used water as a base fluid

Literature Survey

Nurettin Sezer et.al [1], [2019], conducted boiling experiments with Graphene oxide Nanoparticles in water and with mixture of Carbon Nanotubes and Graphene oxide (at 1:10 wt ratio) at very low concentrations and on observation of the heating surfaces after boiling proved that improved surface capillarity, thermal activity and highly porous surface improves the bubble generation rate as compared to that obtained with a single Particle Nanofluid.Mehdi Bahiraei et.al [2] [2019], Used ribs and secondary channels along with a hybrid nano fluid (Graphene-silver Nano particles) to improve the thermal performance of the heat sink but achieved it with penalty in pressure drop. Aabid Hussain Shaik et.al.[3] prepared the Cu-graphene hybrid Nanofuids by dispersing the synthesized Cu nanoparticles and graphene nanoplatelets powders in the base fluid using the ultrasonication method which showed an exceptional stability and improved thermal conductivity. He also used FOM analysis to recommend hybrid nanofluid for laminar flow.M Khayat et.al [4] [2019], found that Hybrid water-based

Nanofluid containing 70% TiO_2 and 30% OH-based MWCNT in volumetric concentrations of 0.5% volumetric concentration gives better thermal performance in a trapezoidal shaped microchannel heater as compared to the other shaped heaters.Mostafzur RM et.al found that [5] , found that thermal conductivity , density and viscosity of Al_2O_3 -MWCNT hybrid Nanofluid/ radiator coolant increased with increase in concentration of Nanoparticles and recommended the use of the said hybrid Nanofluid for solar energy applications.K. Palanisamy et.al[6] was able to improve the Nusselt numbers by 52% at a concentration of 0.5% of MWCNT in a coil type heat exchanger but at the cost of a pressure drop of 81% D Vasudevan et.al [7] [2020], Conducted experiments with MWCNT based nanofluids on a flat plate heater for varying concentration from 0.2 % to 0.8 % and attributed the increase in CHFto the increase in angleof contact (from 98^0 to 130^0) and surface roughness (from 41 nm to 110 nm).Pravin Sharma et.al [9] [2020], obtained a stable and a higher conducting (thermal) hybrid nanofluid made of Ag coated ZnO particles and was able to increase the HTC and CHF by 179.92% and 65.51%, respectively with 0.1% concentrations of Ag/ZnO nanofuids. This was attributed to the increased wettability of the heater surfaces .In another experiment, at the same concentration, Pravin Sharma et.al [91] [2022] was able to further increase the HTC and CHF by 253 % and 80 % respectively by modification of modifying the heater surface and attributed the same to the increased roughness of the surface Kumar V et al[10] tested Al_2O_3 -MWCNT hybrid nanofluid in minichannel heat sink and obtained the best thermohydraulic performance when Al_2O_3 and MWCNT are mixed in the ratio of 3:2.Mehrdad Zolfalizadeh, et al [11] used 0.06% of Graphene Nanoplate (GNP) in water and was able to improve the performance of the heat exchanger by 8.88% Salaheldin ALOUS et.al.[12]Utilized the Multiwalled Carbon Nanotubes (MWCNT), and Graphene Nanoplatelets / water Nanofluid as coolants in Photovoltaic Thermal (PVT) systems and observed that Graphene Nanoplatelets-water nanofluid gave the highest thermal energetic efficiency as compared to the others.Congcong Du 1 et.al. [13] added MWCNT to Fe_3O_4 and observed an increment of Thermal Conductivity for the hybrid Nanofluid by 0.47%.Ramakrishna Hegde et. al [14]2012,Conducted experiments on the Pool boiling of CuO nanofluids on a bare heater of Ni-Cr wire and found that CHF values were affected by the duration of boiling, surface microstructure and concentration of CuO particles.Kartik Srivastav et al. [15]demonstrated that cylindrical brick shape of hybrid nanofluid made of MWCNT-Fe_3O_4 in the ratio of 50:50 used as coolants in Mini channelsgave the superior performance as compared to the other shapes of nanoparticles.Alexandre Melo Oliveira et al. [16] evaluated experimentally the thermophysical properties of the functionalized MWCNT Nanoparticles in distilled water and contributed a valuable database of the properties at different concentrations and different degree of stability Amit Akbriet.al[17, 19] showed that Graphene Nanoplatelet (GNP) based Nanofluid when boiled over a stainless heater gave higher value of CHF as compared to the MWCNT based nanofluid and agree with the Kandlikar correlation . The functionalized GNP based nanofluids demonstrated stability over a long duration of time and gave a higher value of CHF as compared to the GNP based fluids. Sameer Gajghate et.al.[18] was able to improve the boiling of deionized water overa

Graphene coated Copper heater surface and was able to predict the PBHTC fairly well with his developed ANN based model

Amir Vasei Moghadamet.al [20] studied the effect of smooth and grooved heater surfaces on

the boiling performance of MWCNT /water nanofluid and he proved that circular groove inclined at a 45° angle gave better thermal performance as compared to the smoother surface.Shiqi Wang et.al [21], Investigated effect of graphene nanofluids on boiling heat transfer enhancement.Explored mechanism through wettability, roughness, SEM, EDS, and boiling curves.Graphene-MWCNT enhances CHF up to 76.1% at 10 mg/L concentration.Enhanced wettability and reduced surface roughness contribute to heat transfer.

It can be observed from the literature review that correlation of the bubble dynamics with the boiling heat transfer characteristics of hybrid nanofluids at different concentration of Nanoparticles has not been made so far. Hence in this work an attempt has been made to visualize the growth of bubbles during the boiling of hybrid nanofluids made of Carbon Nanotubes and Graphene Nanoparticles using high speed camera. The average diameter of bubbles is obtained using the image j software.The nucleation site density, frequency of bubble generation and maximum bubble diameter is correlated with the boiling heat transfer characteristics obtained at different concentration of Nanoparticles.

2. Nanofluid Preparation and Characterization

Graphene and MWCNT Nanoparticles were purchased from suppliers (Adnano Technologies Pvt. Limited Shimoga, Karnataka). The average diameter of the nanoparticles was less than 30nm. The surface area of Graphene and MWCNT nanoparticles were 100 m^2/g and 260 m^2/g respectively. Thermophysical properties of Graphene and MWCNT as provided by the suppliers are as follows

Table-2.1 Thermophysical properties of Graphene Nanoparticles

Name of the product	**Graphene**
Color	Black
Purity	99%
Diameter Average	10μm
Thickness	5-10nm
Specific surface area	100 m^2/g
True Density	2.267 g/cm^3
Thermal Conductivity	4000 W/m-K

Table-2.2 Thermophysical properties of MWCNT Nanoparticles

Parameter	**Value**
Color	Black
Purity	98%
Diameter	5-15nm
SSA	260 m^2/g
True density	2.1 $g//cm^3$
Thermal Conductivity	3000 W/m-K

2.1PREPARATION OF HYBRID NANOPARTICLES

2.1.1 Two Step Method

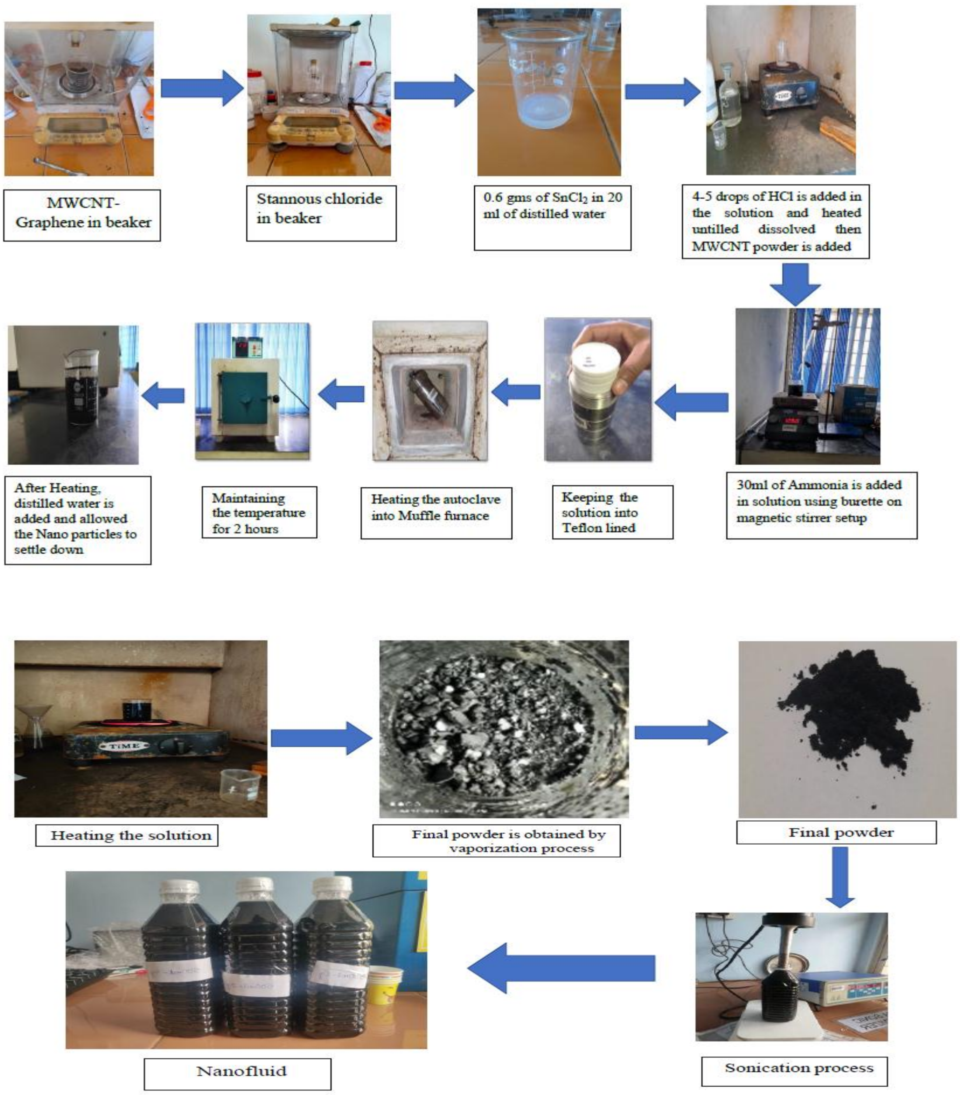


Figure.2.1 Preparation of Nanoparticles for enhancementof thermal properties

2.1 Preparation of Nanoparticles

2.1.1 Two Step Method

In the two step method, the selected nanoparticles are produced in the laboratory or procured from the market and then dispersed in a suitable base fluid to form a nanofluid. Thus, it is simpler than the single step method but the nanoparticles aggregate to form clusters due to their higher value of surface energy. After some time, the particles will clog and sediment at the bottom of container. Partial dispersion of nanoparticles in the two-step method demands higher volume fraction of nanoparticles in the base fluid to compensate for the thermal performance which may decrease. The two-step method works well for the oxide particle and carbon nanotube but not for metallic nanoparticles.

Initially,0.6 grams of Stannous Chloride was taken in a small beaker and to it 20ml of distilled water was added. It was then heated in fume hood furnace so that Stannous Chloride completely dissolves in distilled water. 5-6 drops of concentrated Hydro-Chloride (HCl) is added to above solution so that the powder dissolves completely**.** Desired amount of Graphene and MWCNT was added to the above solution. The 30 ml of Ammonium solution wasthen added to improve the stability of the nanoparticles'Thus prepared solution is placed on magnetic stirrer set up and stirred for 2 hours. After Magnetic stirring process, the solution is filled in the Teflon and heated for 3 hours at constant temperature of 150^0C for heating, so that the nanoparticles completely mix and settles in the solution.

After rinsing the solution with distilled water, the solution is allowed to settle for 2 days so that we get amorphous powder from the solution. Then take out the distilled water from the beaker and allow the nanoparticle to dry for 2 days. Later, the nanoparticles are heated on the heating furnace to remove the moisture content and to make it a completely dry amorphous powder.

2.2 Preparation of Hybrid Nanofluids

Graphene and Multiwalled carbon nanotube nanofluids were generated separately using magnetic stirring at 1000 rpm for two hours. To prevent agglomeration, these fluids were ultrasonically treated for three hours at a constant temperature of 150°C (Oscar Ultrasonics, India).

Hybrid nanofluids are prepared by two-step method [previous researchers]. The weight of nanoparticles was determined from equation (i) for desired volume concentration.

Therefore, % volume Concentration:

$$\%\, VolumeConcentration = \left[\frac{\frac{w_{np}}{\rho_{np}}}{\frac{w_{np}}{\rho_{np}}+\frac{w_{bf}}{\rho_{bf}}}\right] X100 \qquad \textbf{(i)}$$

To properly mix the two types of nanofluids, equal quantities of the single type nanofluids are combined and ultrasonicated for one hour. This results in hybrid nanofluids with weight concentrations of 0.1, 0.2, and 0.4 wt(%).

Figure.2.2 Sonication

Figure.2.3 Prepared Nano fluid

The Nanofluids of Graphene-MWCNT nanoparticles of different concentrations i.e., 0.1 wt(%) , 0.2 wt(%) and 0.4 wt(%) have been prepared separately. 100ml of distilled water is taken in three different beakers and namely A, B and C respectively. After that, 50 ml of nanofluids made from Graphene and MWCNT nanoparticle (of required concentration such as 0.1 %, 0.2 wt(%) and 0.4 wt(%) etc as given in (i) are added to the respective beakers A, B and C. Stirred it well for the proper mixing of nanoparticle with the base fluids and to have better stability and the mixture is placed in the sonication bath for 60 minutes.

2.3 Thermophysical Properties of Hybrid Nanofluids

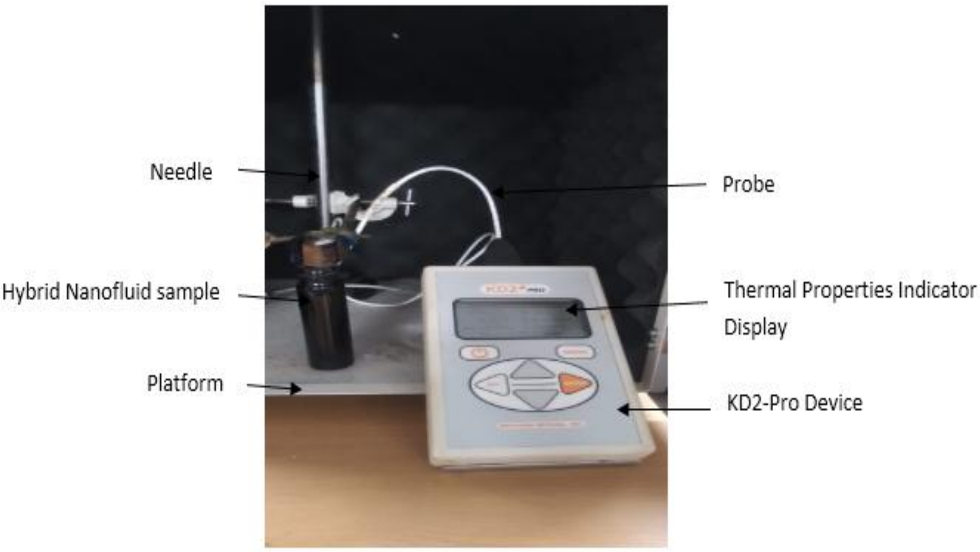


Figure.2.4 KD2-Pro Analyzer

KD2-Pro analyzer was used for the measurement of thermal conductivity. The operation of the device is based on the transient dynamic technique which consists of sensing the temperature rise of a linear hot wire that is connected to the substance whose temperature is to be measured. This instrument is supported by a 60 mm long, 1.3 mm diameter probe. Its accuracy is 5%. The probe is calibrated using pure water as the testing fluid at ambient conditions.

A glass vial with a 30 mm diameter was filled with a 100 ml sample of Hybrid nano fluid. In order to prevent the sensor needle from touching the vial walls, a septum was added to the vial top to enable the needle to penetrate the fluid. Only after a few hours of sonication, the thermal conductivity of every sample was measured. The average of three readings is used for the analysis and is as shown below

Table-2.3 Thermal properties of hybrid Nanofluids at different wt(%) conc.

Samples wt(%)	Thermal conductivity (W/m-K)	Thermal diffusivity (x$10^{-6}m^2/s$)	Specific heat (MJ/m^3-K)	Probing length (m)
0.1	0.6405	1.198	0.08388	0.0196
0.2	0.6617	0.5919	0.2056	0.0138
0.4	0.6807	0.2649	0.4935	0.00921

The table 2.3 shows the thermal properties of Gr-MWCNT hybrid Nanofluids at different concentrations of Nanoparticles. It can be observed that the increase in concentration of nanoparticles added would increase the thermal conductivity of the fluid. The increase in the nanoparticle concentrations would decrease the thermal diffusivity value as more time is required to get measurable temperature difference in the minute size nanoparticles for the depth of probe. The specific heat and thermal diffusivity values are increased with the decrease in the probing depth value which implies that the amount of heat required to raise unit temperature

difference and diffusion of heat through the nanoparticle is more with smaller probing depth. The magnitude of probing depth decreases with the increase in the nanoparticle concentrations.

2.4 Experimental Set-up and Arrangement

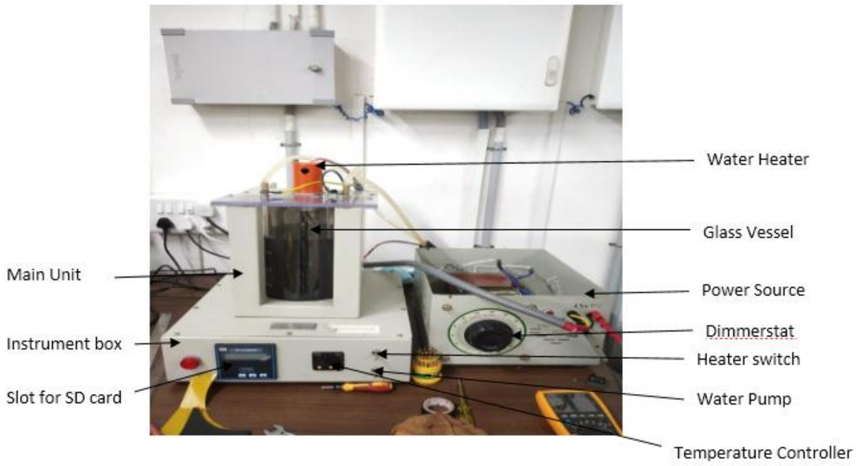


Figure.2.5 Pool Boiling Heat Transfer Setup

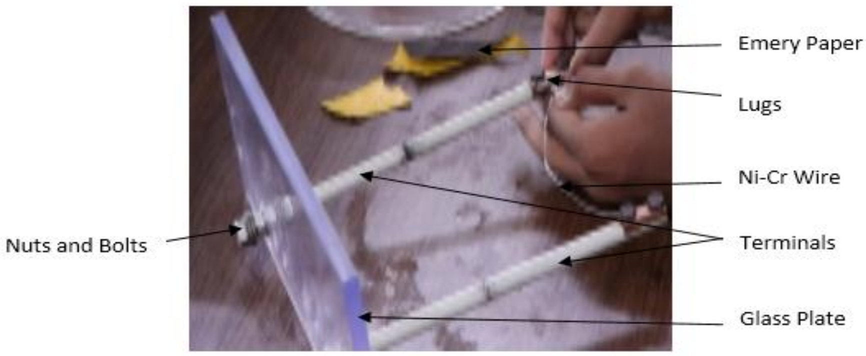


Figure.2.6 Preparation and fixing ofNi-Cr wire on the Copper Electrodes

This new equipment uses electrically heated resistor wire as the heat source. Water purified by the reverse osmosis process or distilled water is used as the fluid. The wire temperature is estimated by taking account the lead resistance. Videography is used for recording the boiling phenomena. A suitable length of the resistance wire is taken and its ends are bent and fixed to the silver coated copper lugs as shown in fig.2.5. The effective length of the wire between the lugs was measured accurately. The connecting flat surfaces from both the leads and the copper shoes were polished regularly to ensure proper electrical contact. The lugs at the end of the resistor wire are then fixed securely to the leads by screws. Nearly 4 litres of distilled water was taken in the beaker. The copper leads, the RTD and the immersion coils are assembled as shown in the figure 2.4. The polarity of the power source and the RTD sensor must be maintained as indicated. Additional illumination may be provided for making good quality video during measurements to capture the boiling phenomena. The micro-SD card is inserted into the VA meter in the slot provided in the front of the meter. The temperature controller is set to the desired level. Voltage is increased continuously and slowly. The rate of increase of the voltage depends on the laboratory conditions. It is suggested that the total time for burnout or maximum current / voltage (limited by the power source) may be achieved in about 10 minutes. After the experiment, SD card from the VA meter is removed and the data transferred to the laptop/PC through an SD card reader (USB device).

The test wire of 0.54 mm diameter and 135 mm length made of Ni-Cr (80:20) was connected to the heater terminals. The test wire was connected to the heater terminals and was placed in the container having the distilled water. The Graphene-Multiwalled Carbon Nanotubes (50:50) hybrid nanofluids of the required concentration in sufficient quantity was taken into container for each experimental trial. Main heater was switched on and water was heated to the desired temperature of 60^0C. The test heater wire was then heated by switching on the test heater wire. The power given to the test heater wire is adjusted and increased in steps by using the dimmerstat.Inserted a SD card into the setup to store the experimental voltage and current data and captured the bubble growth on wire using high resolution camera. Note down the voltage, current, water bath temperature and surface temperature of test wire respectively. Repeat the same experiment for different concentrations of Graphene-MWCNT hybrid nanofluids.The above procedure is repeated for different hybrid nanofluid concentrations. The experimental data stored in SD card was transferred to the computer/laptop for generating the required graphs.Then, Calculated the heat flux and PBHTC. Plotted the various graphs of heat flux versus excess temperature, Boiling heat transfer coefficient versus heat flux, boiling heat transfer coefficient versus wire temperature, heat flux versus wire temperature.

2.6 Characterization of Hybrid Nanofluids

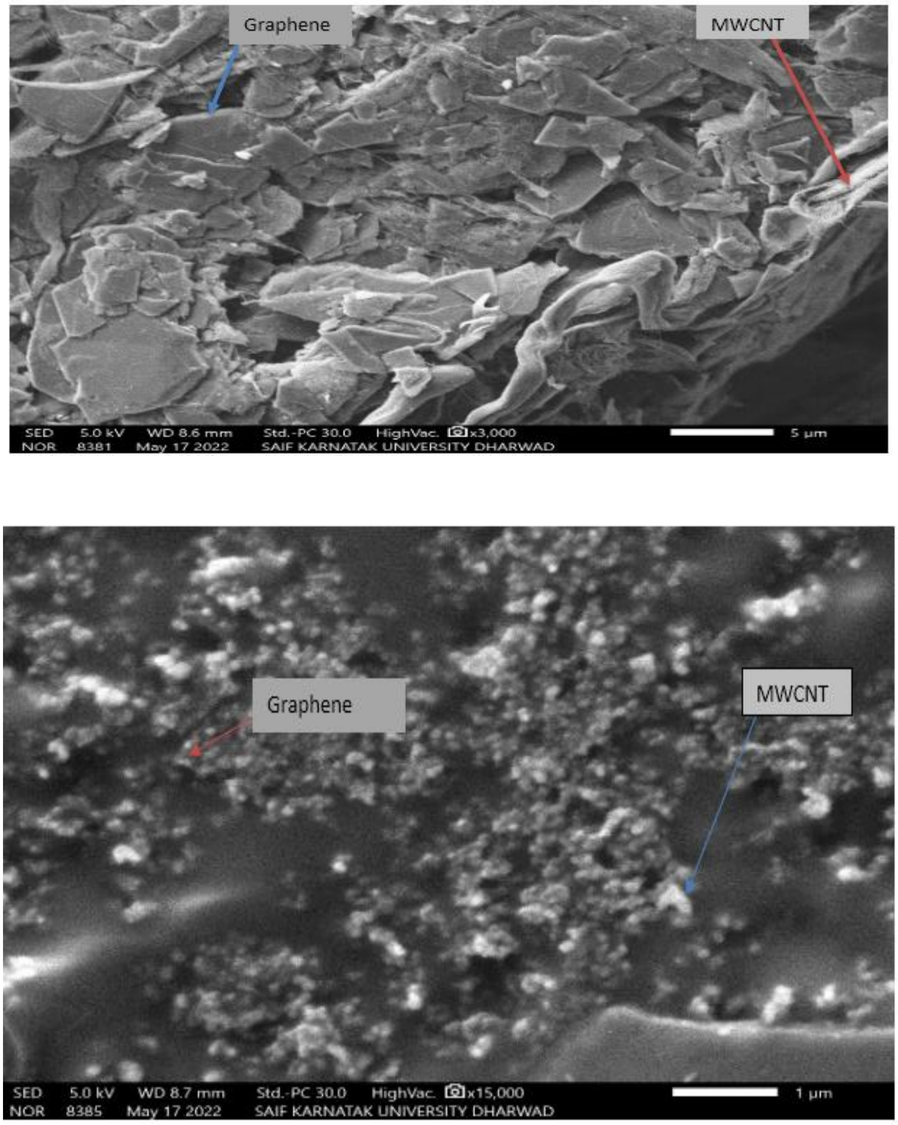


Figure.2.7 SEM images of Graphene-MWCNT hybrid nanoparticles

Figure.2.6 (a, b)shows the morphology of the Grapheneon MWCNT obtained using Scanning Electron Microscopy (SEM).Scanning Electron Microscope (SEM) was conducted using a Std.-PC 30.0 at 5 kV. The MWCNTs coated with properly-dispersed Grapheneparticles shows that the MWCNTs and Graphene had close contact.

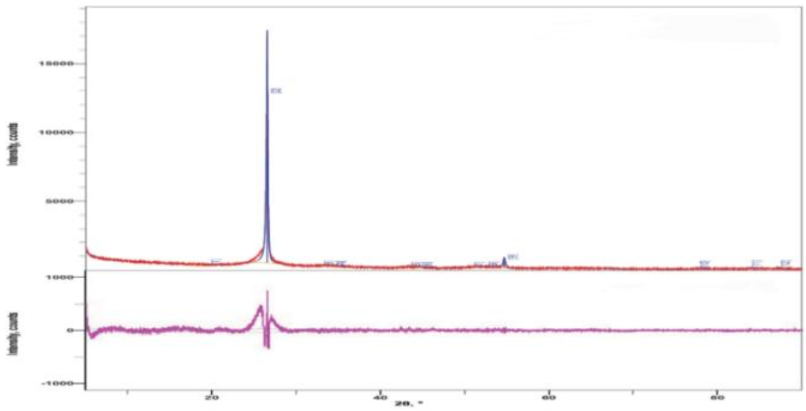


Figure.2.8 X-RD images of Graphene-MWCNT hybrid Nanoparticles

X-Ray Diffraction (XRD) patterns were analyzed using the X-Ray diffractometer (Bruker AXS., Germany) and Cu Ká radiation source at 40 kV. The XRD patterns of Graphene-MWCNT hybrid as shown in Fig. 2.8 reveal only the anatase phase of Graphene. The pristine MWCNTs have two typical (002) and (09) diffraction peaks. For Graphene-MWCNT hybrid, the main diffraction peaks of anatase Graphene (01, 03,04, 05,06,07,08,10,11 and 12) are clearly shown in fig.2.7.

3. Results and Discussions

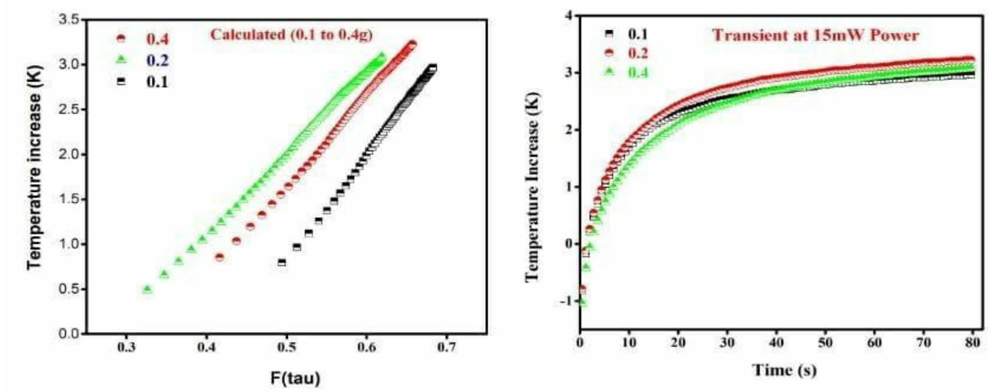


Figure.3.1 Effect of temperature increase on HNFC at 15MW Power

The figure 3.1 shows the variation of temperature and shear stress of the Nanofluids with the addition of heat at different weight concentration of the Nanoparticles (0.1, 0.2 and 0.4 wt.(%)). It can be seen from figure that temperature of the Nanofluids increases over time with the input heat .There is a linear variation of shear stress with increase in temperature can also be seen in the figure. The rate of heat transfer also increases with the temperature rise of the fluids with respect to time, thermal conductivity of fluids and surface area of the fluids.

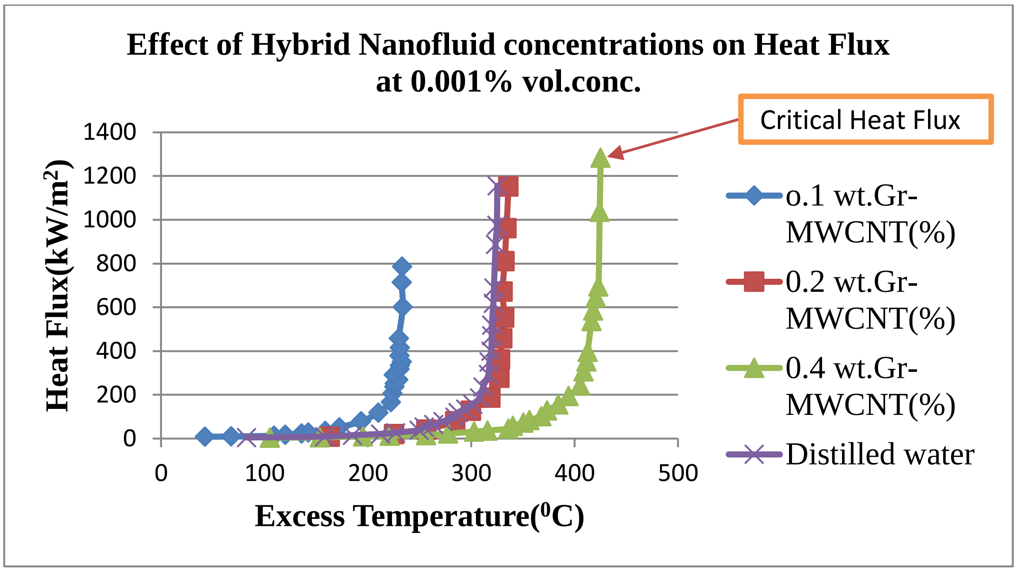


Figure.3.2 Pool boiling curve for Gr-MWCNT/distilled water on Ni-Cr Wire at 0.001% Vol.Conc.

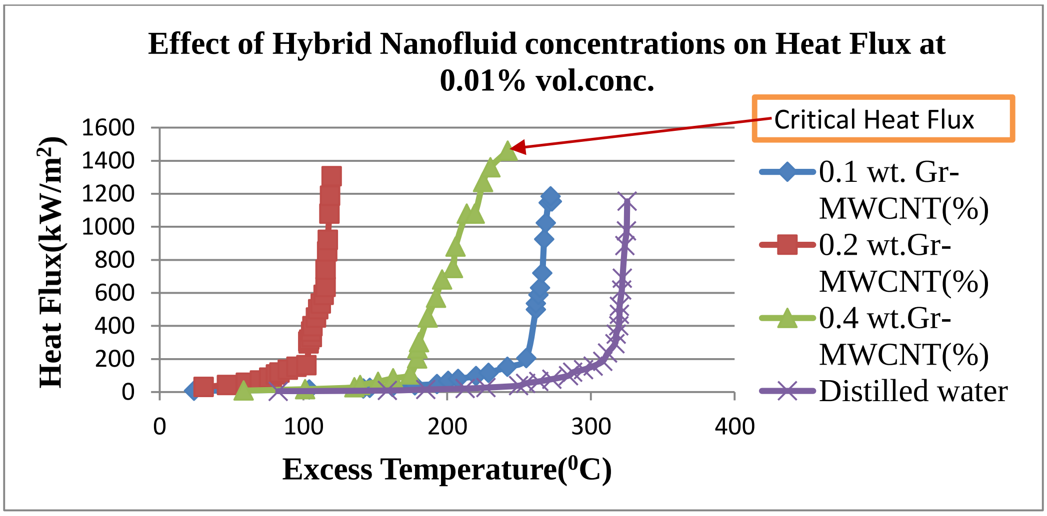


Figure.3.3 Pool boiling curve for Gr-MWCNT/distilled water on Ni-Cr Wire at 0.01% Vol.Conc.

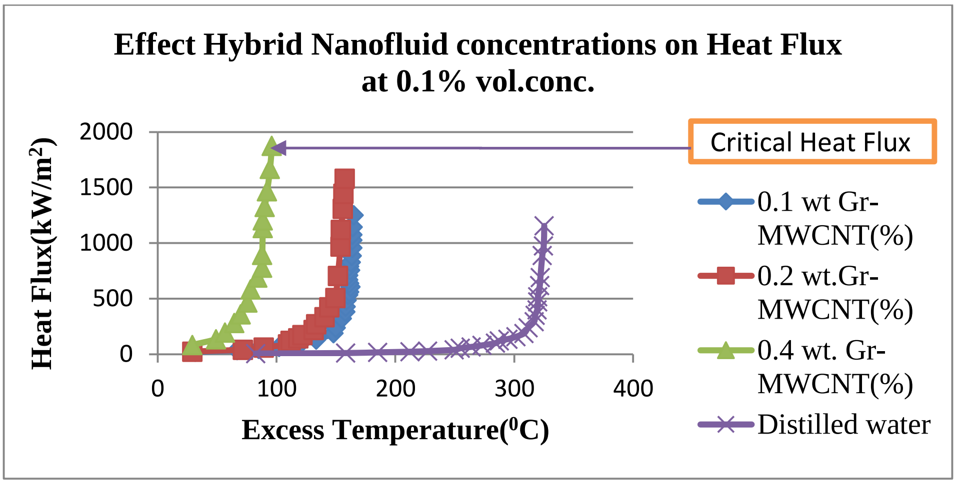


Figure.3.4 Pool boiling curve for Gr-MWCNT/distilled water on Ni-Cr Wire at 0.1% Vol.Conc.

Effect of NanofluidsConcentration on the Pool Boiling Curve

Figures 3.2 to 3.4 shows the effects of variation of Nanoparticles concentration (0.1 %, 0.2 % and 0.4 %) on the pool boiling curves at different volume concentrations (0.001 %, 0.01 % and 0.1 %) respectively. The Critical heat flux (CHF) value is found to increase with the concentration of Nanoparticles in the base fluid. Also, it can be observed at the higher volume fraction of 0.1 % that superheat temperatures in degrees required to attain the CHF value decreases with the increase in concentration of Nanoparticles. This is evident in the table 3.1

Table 3.1 Consolidated Heat Transfer performance of Hybrid nanofluids concentrations

Volume Concentration in percentage (%)	**Concentration of Nanoparticles weight in percentage(%)**	**Maximum heat flux value attained(kW/m^2)**	**Maximum heat transfer co-efficient value attained(kW/m^2-^0C)**	**Excess of temperatures required in ^0C**
0.001	0.1	1124.62	2.91	233.16
	0.2	1151.81	3.09	335.94
	0.4	1283.44	2.78	425.23
0.01	0.1	1184.90	3.84	271.88
	0.2	1305.80	8.38	119.67
	0.4	1460.62	2.68	250.40
0.1	0.1	1249.13	6.21	164.87
	0.2	1578.23	8.15	157.42
	0.4	1874.14	14.20	95.94

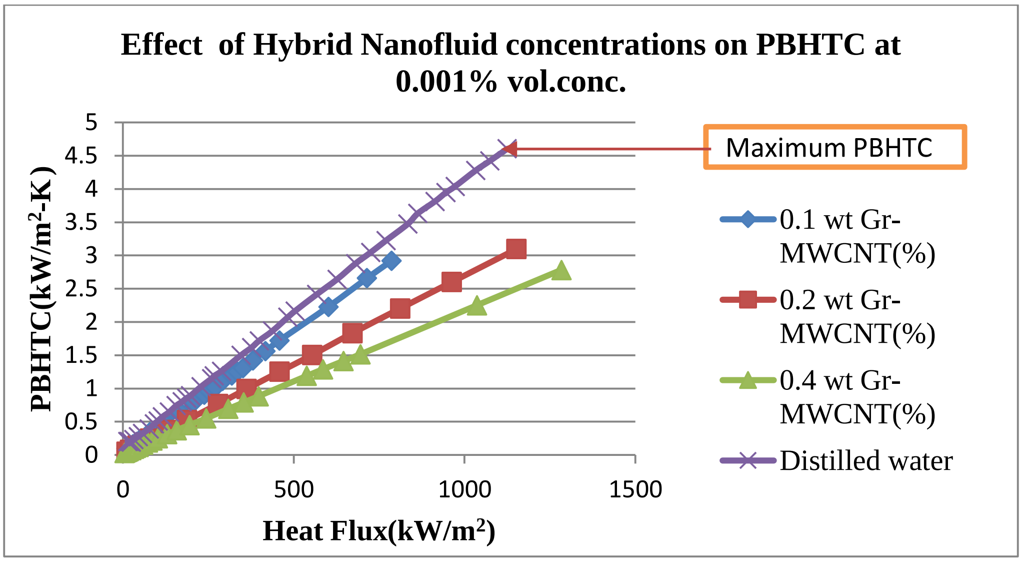


Figure.3.5 Effect of heat flux on PBHTC at 0.001% Gr-MWCNT/distilled water hybrid nanofluid conc.

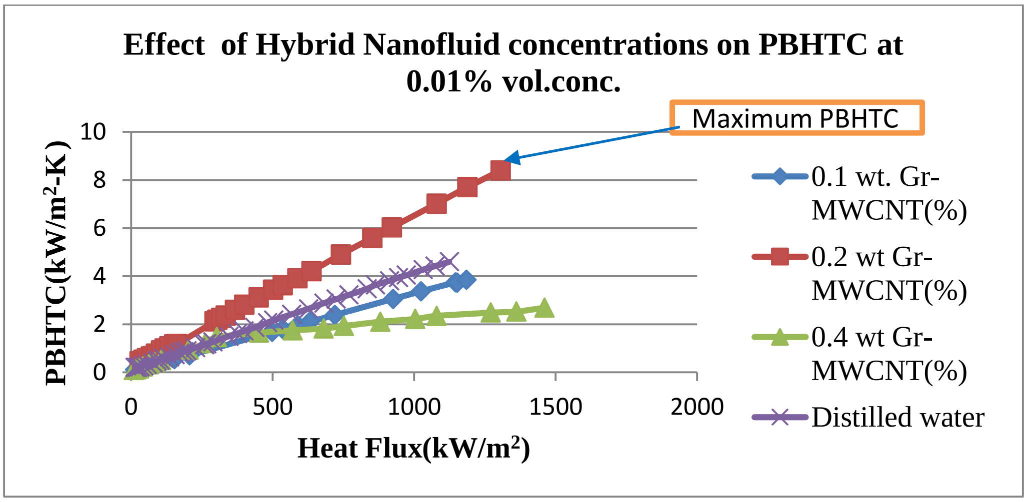


Figure.3.6 Effect of heat flux on PBHTC at 0.01% Gr-MWCNT/distilled water hybrid nanofluidvol. conc.

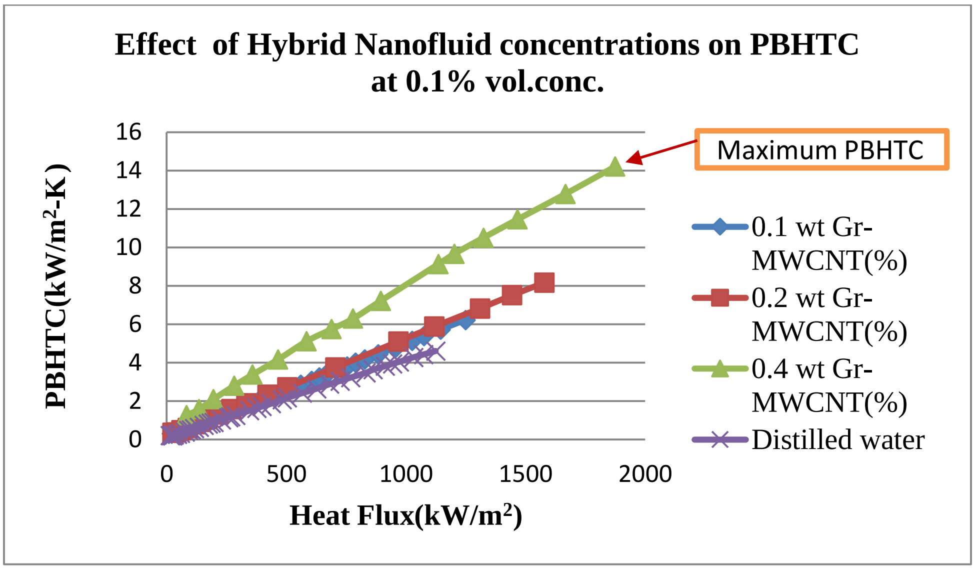


Figure.3.7 Effect of heat flux on PBHTC at 0.1 % Gr-MWCNT/distilled water hybrid nanofluids vol.conc.

Figures 3.5, 3.6 and 3.7 shows the effect of concentrationon Pool boiling heat transfer coefficient (PBHTC).It can be observed that PBHTC values increases with the heat flux at all of the said concentrations.PBHTC values at CHF are 8,500 W/m^{2}K at 0.2 % by mass concentration and14,000 W/m^{2}K at 0.4 % by mass concentration are obtained at the volume concentrations of 0.01 % and 0.1 % respectively.

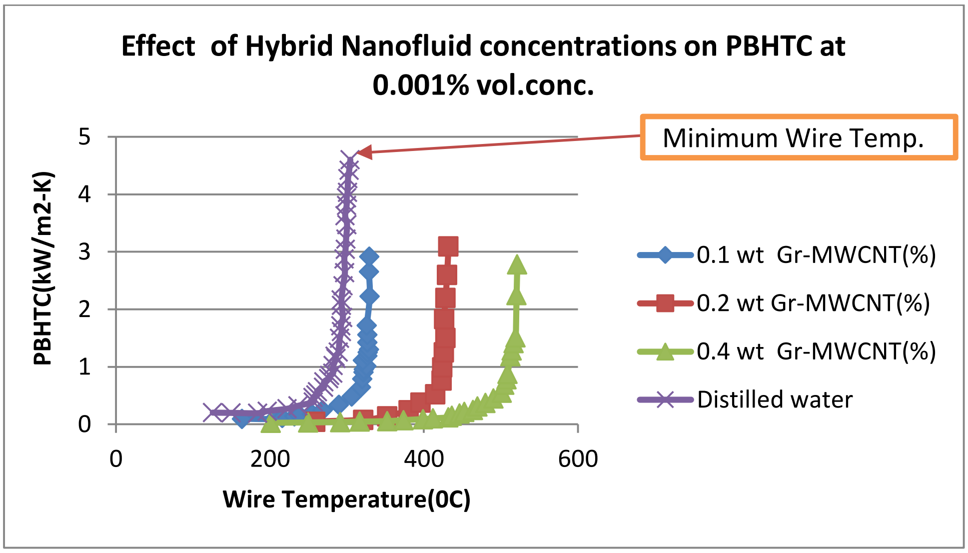


Figure.3.8 Effect of wire temperature on PBHTC at 0.001% Gr-MWCNT/distilled water

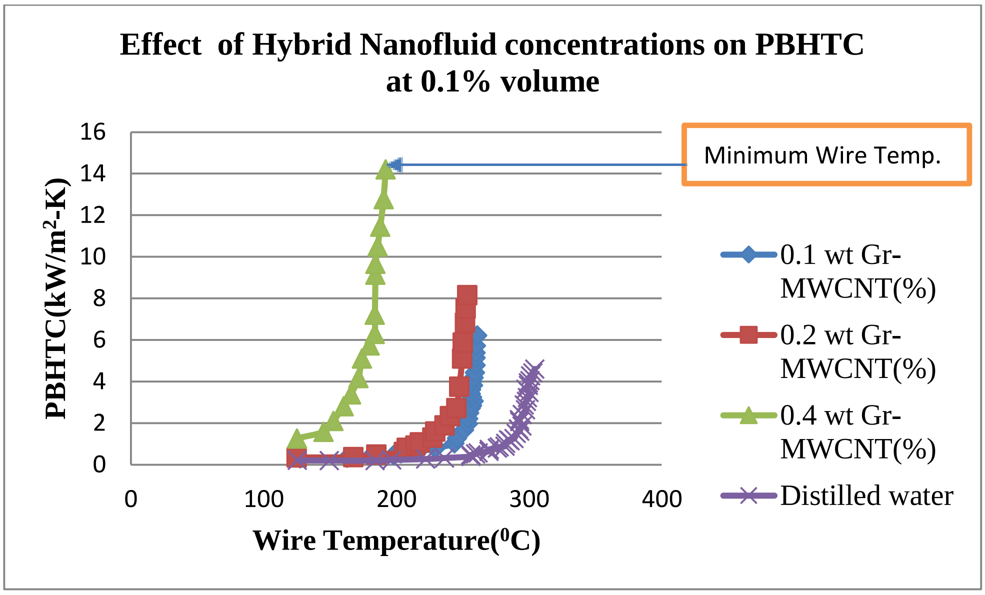


Figure.3.9 Effect of wire temperature on PBHTC at 0.1% Gr-MWCNT/distilled water

Effect of Concentration of Nanoparticles on PBHTC

The effect of deposition of Nanoparticles on the wire temperature and PBHTC of Graphene-MWCNT in distilled water at the volume concentrations of 0.001% and 0.1 % volume concentration respectively is depicted in figures 3.8 and 3.9 respectively. It is observed that wire temperature increases with the concentration of Nanoparticles at lower volume concentration whereas at the higher volume concentration, it is found to decrease.

A layer of Graphene-MWCNT formed on the wire surface may cause the abatement of PBHTC which eventually may cause the temperature of the wire to increase initially at lower volume concentration (of 0.001 %) however wetting of the heater surfaces , increase in contact angle , increase in the diameter of the bubbles occurring at higher volume concentration (0.1 %) causes the PBHTC to increase . More amount of heat gets removed from the heater surface and thus lower superheats are required for the nucleate boiling at higher volume concentration

CHF value is determined from the following equation at different hybrid nanofluid weight concentrations

$$q = \frac{V * I}{\pi * D * L} = \frac{Q}{A_s}\frac{W}{m^2} ---------------(\boldsymbol{i})$$

Where V=Voltage in volts, I =Current in amps, D= diameter of the wire(m), L=Length of the wire (m)

The PBHTC is calculated from the Newton's law convection

$$PBHTC = \frac{Q}{A_s\ (T_s - T_{sat})}\frac{W}{m^2 - K} \quad ---------- \ (\boldsymbol{ii})$$

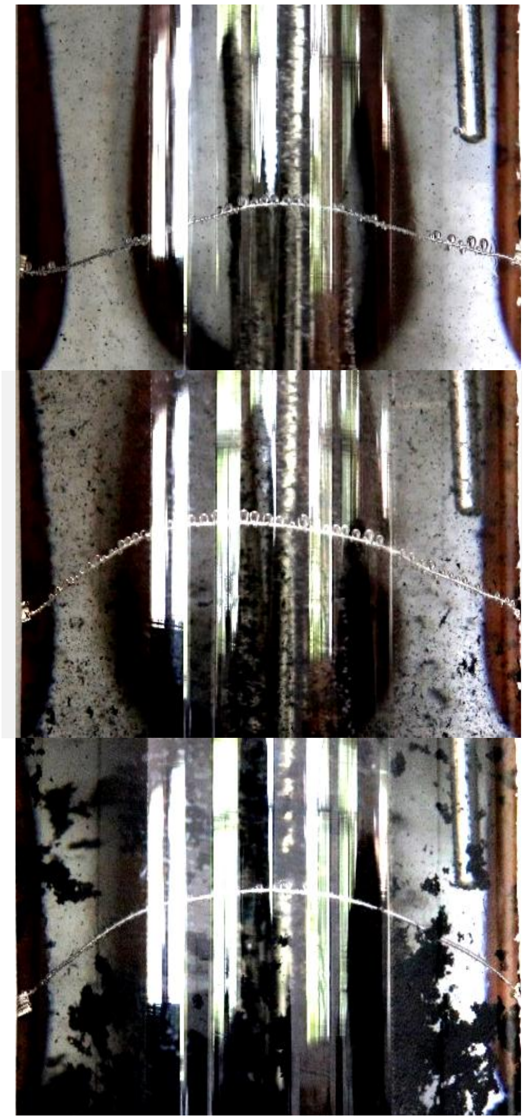
Where Q= rate of heat transfer in watt, A_s=Surface area of the wire (m^2), T_s=Wire temperature (^0C), T_{sat}=Saturation temperature(^0C)

The power input to the wire is calculated from equation

$$P = I^2R\ \ (watt)$$

Where I =Current (Amps)

R= Resistance of the wire($^0C/W$)



g)
CHF=1283.445 KW/m^2
PBHTC=2.78 kW/m^2-K
Average Bubble diameter=1.614mm

h)
CHF= 1460.62 KW/m^2
PBHTC=2.68 kW/m^2-K
Average Bubble diameter=1.681mm

i)
CHF= 1874.14 KW/m^2
PBHTC=14.203 kW/m^2-K
Average bubble diameter=2.358mm

Figure.3.10(g,h,i) Video snapshots and analysis of bubbles using image-J image processing software during Nucleate pool boiling 0.1,0.2 and 0.4 wt.(%) at 0.1% vol.conc. of Graphene-MWCNT/Distilled water.

The figure 3.10 shows the bubbles growth captured during nucleate pool boiling on Ni-Cr wire at 0.1% vol.conc. with 0.1,0.2 and 0.4 wt(%) using slow motion high resolution camera at differentcritical heat fluxes. The average diameter of the bubbles is obtained using the image-Jsoftware. From the above figures, it can be seen that , the increase in nucleation site density , number of bubbles and bubble diameter increases the CHF values and PBHTC .The average diameter of the bubble also increases from 1.614 mm to 2.358 mm withincrease in CHF values and PBHTC values at 0.1 to 0.4 wt.(%)concentration of hybrid nanofluids.

In pool boiling, the rate of heat transfer rate depends on the bubble generation rate and the bubble departure rate from the heatersurface. During the nucleate pool boiling,the bubbles carry away large amount of heat to get transferred to the surrounding fluid. The vapor bubbles generate on the heater surface, grow in size and detach from the surface at higher heater temperatures. The Small bubbles get coalesce and entirely blanket the heating surface at higher heat fluxes fordistilled water.

At the beginning, the deposition of hybrid nanoparticles as nanolayers generates a large number of nucleation sites and bubble generation frequency is increased.Thus, the PBHTC increases with time at thebeginning.But at higher wall superheats and with higher concentration of nanoparticles, more number of particles get trapped in the cavities of the nucleation sites. This disrupts the nucleationprocess and bubble generation frequency on the test surface.Also, the thermal resistance of the test surface is increased with increase in thickness of deposited nanoparticle layer.Thus,the PBHTC gets decreased over the time.

The enhancement of PBHTC and CHF in nucleate pool boiling depends on the heater geometry and cavities (roughness) on the test surface. Whereas quite a few of researchers have claimed the increase in PBHTC and CHF values to the higher thermal conductivity of the nano sized particles with increased surface area.

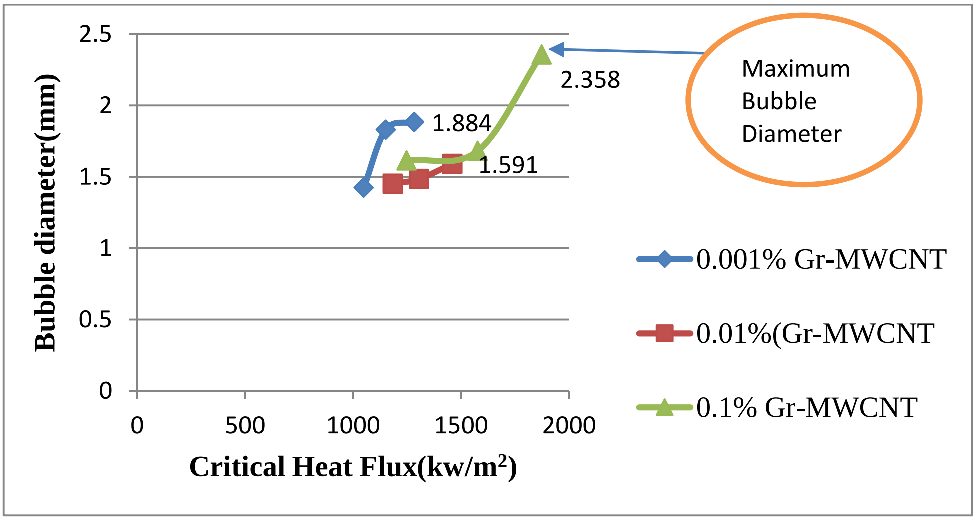


Figure.3.11 Effect of bubble diameter on Critical Heat Flux at hybrid nanofluid conc.

The impact of bubble growth on the CHF values at different concentration of Nanoparticles is shown in figure 3.11. From the above figure, it can be seen that diameter of the bubble increases in proportion to the concentration of Nanoparticles. Also, the effect of the size of the bubbles on the CHF values can also be seen. The maximum diameter of the bubble is 2.36 mm with the corresponding value of CHF value being 1874 kW/m^2.

a) Beginning of nucleation

b) The bubbles grow and depart from the wire

c) End of nucleate boiling

d)Fully developed MEB boiling

e)The density increasing with high heat flux and velocity.

Figure.3.12 Video snapshots showing boiling activity during a test run with Nichromewire and at 60^0C water temperature

The figure 3.12 depicts the video snapshot of Micro-bubble Emission Boiling captured during boiling of hybrid-nanofluid .From the above figure, it is observedthat, the nature of Micro-bubble Emission Boiling with saturated water with non-condensable gases was quite different from that with hybrid nanofluids concentrations. While the MEB was visually observed as a dense cloud soon after the nucleate boiling regime, the microbubbles were not visible to the bare eyesin the case of distilled water. However, the bubble emission was evident from the audio recordings during the tests. The above figure depicts the MEB observed

Conclusion

Experiments were conducted usingGraphene-MWCNT/ distilled water hybrid nanofluid to study the effect of concentration on the pool boiling characteristics along with the visualization of regimes of boiling .From the experimental results, the following conclusions were made,

- The thermophysical properties of Nano fluid increases with the concentration of Nanoparticles which eventually will lead to increase in PBHTC and CHF values. There is also an improvement of thermophysical properties of hybrid nanofluids as compared to the single particle fluids.
- The super heat temperatures required for the nucleate boiling decreases with the use of Graphene-MWCNT/distilled waterhybrid nanofluid as compared with

distilled water. The increase in hybrid nanoparticle concentrationsin base fluid enhanced the CHF values by 12.38%, 23.01%and 39.99% at 0.001, 0.01 and 0.1% volume concentrationsrespectively.

- The maximum enhancement in PBHTC is 67.59% at 0.1% volume concentration ofGraphene-MWCNT/distilled water hybrid nanofluids compared with distilled water at critical heat flux. ThePBHTC decreases with increasing hybrid nanofluid volume concentrationsdue to formation of layer of nanoparticles on the test surface.
- The number of bubbles and average diameter of the bubbles increases with increase in hybrid nanofluid concentrations in the distilled water, this results in the increased CHF values and PBHTC

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