Comparison between Nucleate Pool Boiling Heat Transfer of Graphene Nanoplatelet- and Carbon Nanotube- Based Aqueous Nanofluids

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ABSTRACT: An increase of nucleate pool boiling with the use of different fluid properties has received much attention. In particular, the presence of nanostructures in fluids to enhance boiling was given special consideration. This study compares the effects of graphene nanoplatelet (GNP), functionalized GNP with polyethylene glycol (PEG), and multiwalled carbon nanotube (CNT) nanofluids on the pool boiling heat transfer coefficient and the critical heat flux (CHF). Our findings showed that at the same concentration, CHF for functionalized GNP with PEG (GNP−PEG)/deionized water (DW) nanofluids was higher in comparison with GNP- and CNT-based nanofluids. The CHF of the GNP/DW nanofluids was also higher than that of CNT/DW nanofluids. The CHF of GNP−PEG was 72% greater than that of DW at the concentration of 0.1 wt %. There is good agreement between measured critical heat fluxes and the Kandlikar correlation. In addition, the current results proved that the GNP−PEG/DW nanofluids are highly stable over 3 months at a concentration of 0.1 wt %.

1. INTRODUCTION

Ever since the discovery of zero-dimensional fullerene (C60) and one-dimensional (1-D) carbon nanotubes (CNTs) 20 years ago, carbon materials have received increased attention. In 2004, monolayer two-dimensional graphene was successfully isolated and this instigated a profound global interest because of its unique structural, thermal, and electronic properties, which could enhance the performance of graphene-based nanofluids for many applications.1−5

In recent years, many studies have conducted to explore nanofluids in vapor−liquid flow and single-phase systems. It reported the enhancement in heat transfer coefficients (HTCs) and Nusselt numbers in single-phase applications. Because the latent heat is very high, boiling (liquid−vapor phase change) is known as the most effective heat transfer method.6,7 This method is used in numerous industrial procedures including electronic chip cooling, steam generation, refrigeration, different chemical processes, nuclear reactor cooling, and pressurized water reactors. Pool boiling is considered a more complex method, which is affected by various factors including the thermal characteristics of liquid and vapor phases, saturation temperatures, and orientation, size, and surface properties related to the heater.8

A nanofluid contains nanometer-sized particles (e.g., carbon nanostructures, carbides, metals, or oxides). Because of their thermal and mechanical characteristics and their chemical stability, CNTs, and graphene are favorable augmentatives among different carbon nanostructures for use in heat transfer equipment.9,10

Past research studies11−13 have shown that nanofluids with graphene nanoplatelets (GNPs) and CNTs enhance the critical

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heat flux (CHF) and pool boiling characteristics; however, the HTC decreases for CNTs and often increases for graphene.

2. LITERATURE REVIEW

Many studies have investigated the enhancement of pool boiling of HTC and CHF through various nanofluids. To increase the magnitude of CHF, different nanoparticles such as graphene, TiO$_2$, Al$_2$O$_3$, and CNTs were utilized.\textsuperscript{14–17} Kamatchi and Venkatachalapathy\textsuperscript{18} used reduced graphene oxide water nanofluids/(RGO) to study the behavior of pool boiling CHF in a thin electrically heated Ni–Cr wire. It was seen that adding RGO nanoparticles increases the CHF (145–245\%). Umesh and Raja\textsuperscript{19} conducted pool boiling HTC (BHTC) using CuO/pentane nanofluids in contact with milled and smooth circular brass surfaces (diameter = 20 mm) at the 100 kPa and for a range of heat fluxes from 10 to 100 kW cm$^{-2}$. It was seen that for the CuO/pentane nanofluids at low concentrations of 0.005 vol \% led to an increase of 15–25\% in the HTC. They also showed that as nanoparticle concentrations increased, the enhancement in the HTC decreased. Vafaei\textsuperscript{20} conducted pool boiling to describe how HTC is affected by surface roughness, nanofluid concentrations, and heat flux. It was found that the CHF increased with increase in the nanoparticle concentration. The CHF enhancement, however, decreased as heat flux increased because of the size of large cavities that formed at low heat fluxes and as well as little cavities that were active at high heat fluxes.

Wide range of studies has recently focused on nanofluids using graphene suspensions and CNTs. Milanova and Kumar\textsuperscript{21} studied the nucleate boiling of water-based single-walled CNT suspensions. The suspensions were efficient at both the CHF and improving the nucleate boiling of HTC. Because of the existence of CNTs and surfactants, the surface tension of the nanofluids is lower than the base fluid, which causes an increase in the CHF. With the addition of a surfactant with a weight concentration ratio to CNTs of 1:5, a maximum CHF improvement four times higher than a surfactant to CNT concentration ratio of 1:1 was obtained. Liu et al.\textsuperscript{22} investigated HTC of nucleate pool boiling for water-based nanofluids. Its diameter was 15 nm, and its length was from 5 to 15 \mu m with multiwalled CNTs at concentrations of 0.5–4.0 wt \%. The CNT nanofluids significantly increased the HTC of nucleate boiling and the corresponding CHF than pure water. For comparison, Liu et al. also studied boiling with pure water on a CNTs-coated surface and observed that the CNTs nanofluids provided better increase for both CHF and nucleate HTC\textsuperscript{23}. Park and Kim\textsuperscript{24} stated that at a concentration of 0.001 vol \% multi-walled CNTs the nanofluids optimally increased the CHF and HTC of nucleate boiling. Park and Jung\textsuperscript{25} concluded up to 30% rise in HTC of the nucleate boiling using hydrochlorofluorocarbon better known as R22-and water-based 1.0 vol \% CNT nanofluids. Park et al.\textsuperscript{26} examined the CHF improvements using a water-based 0.0001 vol \% graphene oxide (GO) nanofluid. It was found that GO nanofluids are constant in complex cooling configuration. Kamatchi and Venkatachalapathy\textsuperscript{27} showed that as concentration increases from 0.01 to 0.3 g/L, a 145–245\% increase in the CHF could be achieved with RGO nanofluids. Ahn et al.\textsuperscript{28} investigated the increasing potential of RGO suspensions in water that was chemically treated with hydrazine. The aim of the chemical treatment was to create various steps of flakiness in the deposited layer for various RGO concentrations during nucleate boiling. The results indicated that the increased fluid thermal conductivity resulted in boiling to begin earlier in comparison to the base fluid. In addition, it was found that increased RGO concentrations agree with nucleate boiling heat transfer, which was credited to thermal resistance from the thickly aggregated graphene layer (TGL) forming on the heating surface. Ahn et al.\textsuperscript{29} found a significant boiling phenomenon for RGO colloids. In contrast to the fast increase in CHF wall temperature in pure water, the wall temperature for RGO colloids enhanced too smoothly, while wall heat flux was remained at the CHF. This issue postponed dry/hot spot formation, resulting from heat-spreading action in the base graphene layer and self-assembled foam, and the useful impact of boiling in a spongy medium. Kathiravan et al.\textsuperscript{30} performed a comparison between the nucleate boiling efficiency of water-based CNTs nanofluids from 0.25 to 1.0 vol \% (concentrations range). It was conducted with and without the addition of 9.0 wt \% sodium lauryl sulfate surfactant. In case of stable heat flux of 50 W/cm$^2$, it was seen a 1.5, 2.6, and 3.0-fold rise in HTC of nucleate boiling with nanofluids without surfactant at CNT concentrations of 0.25, 0.5, and 1.0 vol \%, respectively (than pure water). Sulaiman et al.\textsuperscript{31} found the same results with SiO$_2$ nanofluids that were credited to the little separation of the nanoparticle deposition layer at high heat fluxes nearing.

In this study, GNP, CNTs, and functionalized GNP with polyethylene glycol (GNP–PEG) nanofluids were synthesized in weight concentrations of 0.01 wt, 0.05 wt, and 0.1 wt \%. Then, the nucleate pool boiling of above-mentioned nanofluids is compared with deionized water (DW). Also, the thermal conductivity of nanofluids and the surface characterization were investigated.

3. MATERIALS AND METHODS

3.1. Materials. For performing this study, GNP (diameter $= 1–20 \mu m$, thickness $= less than 40$ nm) and multiwalled CNTs (length $= 5–10 \mu m$, average diameter $= f 20–30$ nm, tube) were purchased from Vira Carbon Nano Materials (VCN Materials Co., Ltd.). Also, dimethylformamide (DMF), PEG, hydrochloric acid, and aluminum chloride were acquired from Merck, Ind.

3.2. Preparation of Nanoﬂuids. CNT- and GNP-based nanofluids with weight concentrations of 0.01, 0.05, and 0.1% in a base fluid were prepared using a two-step method. The process was started by mixing GNP at given weight percentages with DW, so that a consistent suspension might be achieved. This was followed by an ultrasonic bath (200 W, 4 L capacity, 60 kHz) to create homogenous samples in 2 h. Functionalization of CNT and GNP was performed non-covalently or covalently. CNT and GNP are treated with various functional groups including different surfactants [PVP, gum Arabic (GA), SDBS, and etc.] for noncovalent functionalization.\textsuperscript{32–34} Furthermore, GA was used as a noncovalent group. Its ratio was 1–1 because of CNT in DW and the low dispersivity of pristine GNP.\textsuperscript{30} Then after, the functionalization method was employed using covalent groups. It should be noted that functionalization, which was used for the synthesis of PEG-based GNP, was described by Amiri et al.\textsuperscript{32–34} Figure 1 schematically shows the preparation techniques for GNP/DW and CNT/DW as noncovalent nanofluids and GNP–PEG/DW as a covalent nanofluid. In the current study, agate mortar received AlCl$_3$ as a Lewis acid (184.5 mg). Raw GNP (10 mg) was then mixed for a few minutes. Subsequently, the resulting mixture with 10 mL PEG was dispersed in a Teflon vessel, followed by sonication at 50
°C for 30 min to obtain a stable suspension. Then, by adding one drop of 0.5 mL concentrated hydrochloric acid, sonication was carried out. In the next step, the mixture temperature was increased to 120 °C in a microwave (Milestone Micro SYNTH programmable microwave system) for 30 min using a 700 W. As reaction completed, it showed a reducing trend for the temperature of the final product to room temperature. In addition, the mixture was filtered by a thin layer of Teflon membrane. To remove any unreacted material, DMF and copious amounts of DW were used. Then, the mixture was dried by a vacuum at 50 °C. Figure 2 shows schematic of GNP functionalization processes with PEG.

3.3. Experimental Setup. Figure 3 depicts pool boiling setup experimentally. It was planned to run pool boiling experiments in order to measure the CHF and boiling heat transfer under atmospheric pressure. This setup is comprised of four major components: (a) monitoring system and power control, (b) boiling vessel, (c) section to test sample (boiling surface), and (d) section of heating.

The boiling vessel was a 300 mm × 150 mm × 150 mm rectangular. It was made of Pyrex with proper thermal resistance. The boiling vessel had four observation windows and would allow for setting the test section horizontally so that it is visible boiling phenomena on the test heater. A hole was prepared at the bottom of the vessel in which the major heater was mounted (stainless steel heater block). A tiny Teflon layer was used to ban heat loss and liquid leakage between the hole and the block heater.

The section of heating was a S.S. heater block with four cartridge heaters. Each cartridge heater had a height of 90 mm and a maximum heating power of 700 W. The top of the main pool chamber was mounted by a reflux condenser in order to avoid DW evaporation.

Because rock wool and Teflon were used for the insulation of the S.S. block (owe to low thermal conductivity of 0.03–0.25 W/m·K), the heat transfer through the block is made simple as the one-D steady-state conduction heat transfer problem. This assumption was verified during the experiment when the temperatures of thermocouples 3 and 5 were the same (Figure 4). The section of testing samples was situated on top of a cylindrical S.S. block with a diameter of 40 mm at the bottom of the pool (Figures 3 and 4). The roughness of the test surface was prepared to less than 1 μm. Using conduction from the heating section, test samples were heated, which was comprised of four cartridge heaters. All parts of the experimental setup and S.S. block were insulated to minimize heat loss using Teflon and rock wool.

The bulk temperature was retained at 100 °C through the auxiliary heater feedback control based on thermocouple readings during the experiment, that is, the whole boiling vessel was heated initially using an external auxiliary heater around the vessel before the boiling starts to make sure that the bulk test fluid was at a temperature lower the boiling temperature.

Monitoring system and power control included the following devices. Five K-type thermocouples \( (T_1, T_2, T_3, T_4, \text{and } T_5) \) were inserted in the S.S. cylinder (Figure 4) in order to monitor temperature. Because the distance between the thermal conductivity of the S.S. heater block and thermocouples was clear, using measured temperature, the heat flux through the test surface \( (T_{wall}) \) was calculated according to the Fourier law. Through the extrapolation, the surface temperature was found. Four thermocouples were located at various locations points in the fluid to check the local temperature.

Data collection for heat flux and thermocouple temperatures was performed using a data acquisition system (Dataloger-CUP110). A dc power supply [contact voltage regulator of 20 kW (OMGV20K-1P)] displayed various input powers and regulated the heater surface temperature. The boiling apparatus including condenser, vessel, and pipes was fully insulated to decrease unclearly in the setup. The top of the vessel was installed by a condenser (a safety valve and a copper tube) in order to condense the vapor into a liquid and control pressure and condense the vapor into a liquid.

3.4. Data Reduction and Uncertainty. It is vital to estimate the uncertainties in HTC measurements and heat flux

Figure 1. Schematic of the preparation of covalent and noncovalent for GNP and CNT nano fluids.

Figure 2. Schematic illustration of the functionalized of GNP with PEG.
in these experiments. In this study, the method created by Jaikumar et al.\textsuperscript{16} was used to calculate uncertainties. The thermocouple calibration, the thermal conductivity of stainless steel, and the distances between thermocouples all have a certain error in calculations.

In this study, heat loss was calculated to make sure that heat is transferred through 1-D conduction to the test surface. It was predicted (based on Fourier law of heat conduction) that the temperature profile is linear across the test section was. This assumption was validated as the temperature of thermocouples 4 and 5 was the same as thermocouple 3.

Figure 5 presents the temperature distribution for heat fluxes of 393, 114, and 519 kW/m\textsuperscript{2}, which was plotted between T\textsubscript{1} and T\textsubscript{3} for the test surface. Figure 5 depicts a linear improvement with R squared value near to 1, showing very little heat loss during the experiments.

Two errors happen during experiment; the bias error as consequence of calibration and exactness errors due to sensitivity of testing devices. The total errors are

\[ U_j = \sqrt{B_j^2 + P_j^2} \]  

(1)

\( U_j \) is the uncertainty and \( B_j \) and \( P_j \) are the bias and precision errors, respectively. Thermocouple calibrations, stainless steel thermal conductivity, and the distance between thermocouples on the test chip were the error parameters. The thermocouple exactness error was obtained statistically as ±0.1 °C.

The evaluation of heated surface temperature (\( T_{sw} \)) was performed via the heater temperature (\( T_{th} \)), which is

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**Figure 3.** Schematic of the pool boiling setup.

**Figure 4.** Details of the geometrical properties of the heater surface and heater block.

**Figure 5.** Temperature distributions at different heat fluxes measured between T3 and T1.
measured by the heat flux ($q''$) and thermocouple. Its issue was due to the fact that the measurement of temperature at the heated surface is affected by the bubble growth process because of variations in the heated surface geometry. The temperature of the heated surface was evaluated using a 1-D heat conduction equation. The heat flux was assumed to be transferred in the axial direction. Accordingly, the heat flux is given as

$$ q'' = -k \frac{dT}{dx} \quad (2) $$

The temperature gradient $dT/dx$ was obtained using a three-point backward Taylor series

$$ \frac{dT}{dx} = \frac{3T_1 - 4T_2 + T_3}{2\Delta x} \quad (3) $$

where $T_1$, $T_2$, and $T_3$ were the temperatures corresponding to the test chip bottom, middle, and top, respectively. Using eq 2, the boiling surface temperature is given as

$$ T_w = T_1 - \frac{x_1}{k} q'' \quad (4) $$

where $T_w$ is the temperature of the boiling surface, $k$ is the thermal conductivity, and $x_1$ is the distance between the boiling surface. For all test surfaces, $x_1$ was 1 mm (see Figure 4).

In eq 4, $q''$ is the heat flux that was obtained using

$$ q'' = \frac{V_{\text{heater}} I_{\text{circuit}}}{A_{\text{surf}}} \quad (5) $$

where $V_{\text{heater}}$ is the voltage, $I_{\text{circuit}}$ is an electric current of the experimental heater, and $A_{\text{surf}}$ is the area of the heated surface.

The insulation of the test section heater was done using rock wool and Teflon, and thus the dominant heat transfer mechanism was a 1-D conduction heat transfer. The heat fluxes from eqs 4 and 5 were compared to show the heat loss along the heater block.17 The surface temperature of the test heater surface was extrapolated to calculate the HTUC of pool boiling. The pool BHTC is an indicator of nanofluid thermal performance, which was obtained using

$$ h = \frac{q''}{T_w - T_{\text{sat}}} \quad (6) $$

where $T_w$ is the temperature at the heated surface, and $T_{\text{sat}}$ is saturation temperature. The uncertainties for heat flux and the BHTC were obtained as follows

$$ \frac{U_q}{q''} = \sum \left( \frac{U_{T_1} - T_1}{T_1 - T_3} \right)^2 + \left( \frac{U_{Z_1} - Z_1}{Z_1 - Z_3} \right)^2 + \left( \frac{U_k}{k} \right)^2 \quad (7) $$

$$ \frac{U_h}{h} = \sqrt{\sum \left( \frac{U_q}{q''} \right)^2 + \frac{U_{\Delta T}}{\Delta T}^2 } \quad (8) $$

where $U$ is the experimental error that is defined based on all relevant parameters such as $q''$, $h$, $T$, $k$, and $\Delta T$. The multimeter readings and thermocouples were carried out three times to make sure data reproducibility. Thermocouples showed the maximum deviation of measurement at about 0.1%. Table 1 summarizes the uncertainties for measurement devices employed in the current study.

According to the measurement accuracy displayed in Table 1 and using eqs 7 and 8, the maximum error for BHTC and heat flux was 9.3 and 3.53%, respectively. Figure 6 shows the computed uncertainty percentages for heat flux and boiling heat transfer. With the increase in thermal flux, the temperature differences increase and the uncertainty percentage decreases. Thus, for heat fluxes higher than 600 kw/m²K, heat flux uncertainty is 2.4%, and the BHTC was 6.92%.

### 4. RESULTS AND DISCUSSION

#### 4.1. Thermal Conductivity of Nanofluids

Typically, the thermal conductivity of nanofluids is higher compared with that of base fluids and it enhances with the growth of nanoparticle concentration; thus, the heat transfer properties of base fluids are less than nanofluids. Therefore, it makes them to be a proper selection for heat transfer applications.36 A KD2 Pro device (Decagon devices, Inc., USA) measured the nanofluid thermal conductivity in the temperature (20-60 °C). A transient short hot-wire method was employed. As a test fluid, DW was utilized to calibrate the experimental setup before testing nanofluid.37,38 The nanofluid sample was poured into a glass container and retained in a circulating DW bath system at a stable temperature (capacity: 5 L, Make: JEIO Tech, Korea, temperature stability: ±0.05/0.09 °C, temperature: −25 to +150 °C). It is worth mentioning that the thermal conductivity of each nanofluid was measured five times for various weight fractions of GNP and CNT at temperatures from 20 to 60 °C. That is, on average, five data points were reported. The thermal conductivities of CNT/DW and GNP/DW nanofluids are depicted in Figure 7. The results indicate that with increased temperatures, the thermal conductivity of DW, pristine CNT, and GNP and functionalized GNP with PEG (GNP−PEG)-bases DW nanofluids at all concentrations vary from 0.1% to 10.0% due to the bubble growth process.
increased. It is evident that the thermal conductivity of the base fluid and nano fluids is dependent on both temperature and weight fraction (wt %).

With the increase of temperature increases (20–60 °C) and concentration (0.01–0.1 wt %), growth of the thermal conductivity was observed for all samples. The progression for PEG-functionalized GNP nano fluids was significantly more than the raw GNP and CNT nano fluids. This issue suggests that graphene nano fluids can enhance thermal conductivity with the growth of temperature and concentration (up to 0.1 wt %). Brownian motion can explain this trend based on the random motion of the nanoparticles in base fluid, which move at a higher intensity when temperature increases. This may also be because of the increased destruction of functional groups through the growth of temperature because samples with higher concentration include more functional groups. Through little omitting of functional groups from graphene, the distribution of nanosheets is decreased with a slight growth in conduction conductivity. The present thermal conductivity data related to various samples are consistent with the results obtained by Baby and Ramaprabhu and Ghozatloo et al. and other studies.40,41

Figure 7 expresses the higher thermal conductivity of PEG-functionalized graphene (0.1 wt %) compared with other samples. In addition, with the increase of nano fluid temperatures, the highest percentage of change (about 20%) of thermal conductivity is observed for the GNP−PEG nano fluid (0.1 wt %). The GNP−PEG nano fluid (0.1 wt %) also shows the highest percentage of increase in thermal conductivity than DW (near 20%) at the maximum operating temperature of 60 °C. The percentage of increase for raw GNP nano fluids and CNT is 9 and 6%, respectively, at the same concentration. According to Akbari et al., a two-fold increase in GNP concentration and a tenfold increase in CNT concentration are required to equally enhance the thermal conductivity for GNP functionalized with PEG.

4.2. Surface Characterization. Vessel cleaning is a significant step. This is due to the fact that following the nano fluid tests and all surfaces included in the experimental setup are covered with a deposit of a small number of nanoparticles. These deposits may distort the progress of the nucleate boiling regime and the corresponding CHF in the DW tests (even with low GNP or CNT concentrations). Here, cleaning was done according to the protocol introduced by Mourgues et al. As indicated in Figure 8, pictures (8a–d) display the test surfaces (stainless steel 316) before and after the boiling process for different nanofluids.

Figure 8. Pictures of the test surface (a) before boiling, (b) CNT/ DW, (c) GNP/DW, and (d) GNPPEG/DW nano fluids (0.1 wt %).

It is known that because of the deposition layer, the contact angle decreased. It may be worth mentioning that for the pristine and functionalized GNP nano fluids, the contact angle decreases much more than that for the CNT nano fluids. The decreasing trend of the contact angle causes the liquid drop to spread on the surface so that more of the surface is in contact with the liquid drop. The deposition layer is porous, so it is expected that capillary wicking action would occur in this layer. Then, the porous layer absorbs liquid, and liquid inflows are generated. Therefore, more liquid is captured in the porous layer at lower contact angles.

4.3. Pool Boiling and CHF Results. While increased nano fluid thermal conductivity is attractive, it is not sufficient for its large-scale use in cooling applications. The value of such fluids depends on the boiling characteristics under various conditions.

Because base fluids have less thermal conductivity than nano fluids, the heat transfer characteristics of nano fluids are more favorable compared with base fluids. The boiling is a greatly efficient and common mode of heat transfer. In the boiling process, a liquid transforms into vapor over a hot surface and takes away huge thermal energy with a little temperature diversity.

To examine the reliability of the present laboratory apparatus, a comparison was carried out between prediction correlations of Rohsenow’s and the experimental results for the nucleate pool boiling heat transfer of DW. This correlation expresses that the major heat transfer mechanism is the convection strength in nucleate boiling conditions. This is because of turbulence from bubble vapor (fluid is at saturated condition).

Figure 9 compares the present experimental data for heat versus superheat temperature for DW with the Rohsenow’s correlation. The experimental results for the boiling curve as a
function of the superheat on the surface were consistent with the predictions of Rohsenow.\textsuperscript{52} The mean absolute percentage error (MAPE) was about 14.26\% for heat flux diversities. Figure 9 also shows that high MAPE is nearly 19\% at low heat flux, while low MAPE was about 11 for high and moderate heat flux conditions. The small differences observed between the prediction of the Rohsenow equation and the experimental data. This is because of fluid thermal characteristics and the initial parameters of the equation such as heat flux and so on.

The maximum heat flux is considered as the critical heat flux (CHF). In this amount of nucleate, high cooling efficiency is incurred through boiling heat transfer. The best CHF amount is normal while the contact angle is approximately zero. Capillary action significantly improves the heat transfer at angles.\textsuperscript{53} Thus, it is expected that more CHF improvements are found out at higher weight concentrations, which is consistent with our findings. The impact of surface wettability for graphene/GO nanofluids and alumina–water nanofluid was examined by Park et al.\textsuperscript{54} However, no relationship between surface wettability and CHF enhancement was found. H. D. Kim and M. H. Kim\textsuperscript{55} suggested that capillary wicking on the nanoporous layer causes dry out to be delayed and cools the dry spot, leading to the CHF improvement. Ahn et al.\textsuperscript{56} reported that during RGO nucleate boiling, water absorption could play a role in the saturated porous layer. The results show that CHF enhanced up to 320\%. Nevertheless, they stated that capillary wicking alone cannot explain the mechanism behind the unusual increase of around 320\% in CHF. Although the described mechanism may justify the CHF increment for nanofluid, more studies need to determine the precise mechanism for the unusual increase of CHF in other nanofluids.

To carry out the tests for obtaining the CHF requires high heat fluxes, which is an important technical challenge. As a matter of fact, under atmospheric conditions, the CHF for the clean heating surface and DW is 700–1400 kW/m\(^2\), which can be achieved by a nanofluid with a heat flux of 2000 kW/m\(^2\) or higher as reported in the literature. To this end, some studies recommended a direct electric heating system using a surface or wire where the calculations for wall temperature and heat flux are based on the changes in electrical resistance and input power.\textsuperscript{41} In this situation, samples are normally fractured while the CHF is achieved. This is due to the fact that the sample temperature rapidly goes beyond the ranges of its constituent materials.

The present experimental setup pursues the technique used by Mourgues et al.\textsuperscript{50} The experiments elucidated the pool boiling of CNT and GNP nanofluids. The dispersion of CNT and GNP was performed in DW at different concentrations (0.01, 0.05, 0.1\%). Figure 10 displays the results obtained experimentally for heat flux versus superheat temperature for CNT, GNP, and GNP–PEG nanofluids at different weight fractions. As shown in Figure 10, graphene nanofluids and the boiling heat transfer performance of CNT are higher compared with DW for all concentrations. The critical heat flux of GNP–PEG was amended by 72\% over DW at the maximum level (0.1 wt \% GNP–PEG). As the concentration increased (for raw GNP and functionalized GNP with PEG), the boiling heat transfer performance of GNP nanofluids increases. However, the CHF of CNT nanofluid decreases at the concentrations from 0.01 to 0.1 wt \%. At the same superheat temperature, heat flux increases for GNP and CNT nanofluids more than DW, in particular, for functionalized GNP nanofluids. Additionally, at the same concentration, the CHF of the CNT and GNP nanofluids was less than functionalized GNP nanofluids, and the CHF of the CNT nanofluids was less than GNP nanofluids.

In Figure 11, the pool BHTC of CNT and GNP nanofluids is shown versus heat flux experimentally quantified at various particle mass concentrations. With the growth of the heat flux in the boiling surface, the HTC ascended considerably. It is

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure9.png}
\caption{Comparison of heat flux as a function of difference superheat temperatures for experimental data with Rohsenow’s correlation of the DW.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure10.png}
\caption{Heat flux in boiling conditions versus superheat temperature and CHF values of nanofluids.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure11.png}
\caption{Heat transfer coefficient vs heat flux and critical heat flux values of nanofluids.}
\end{figure}
conjectured that a growth of heat flux amends the rate heat transfer to the surface and bubble formation. Therefore, the bubble interaction, local agitation, and micro/macro convection streams surrounding the bubbles are intensified. Increase in the weight concentration of GNP nanofluids improves the HTC while the increase rate for the HTC in the low heat flux area was smaller than the high and moderate heat flux areas. For CNT, the HTC decreased as weight concentration was increased. On the other hand, the HTC for pristine GNP nanofluids is more compared with DW. This may be because of the Brownian motion of GNP inside the bulk of the nanofluids, the internal thermal conductivity of the GNP nanofluids, and thermal diffusion from the surface to the bulk of the nanofluids. With the growth of heat flux, the gap between the HTC of GNP/DW nanofluids was increased as DW and noncovalent nanofluid (Figure 11).

Obviously, free convection before the CHF is considered as the major mechanism in pool boiling heat transfer. A fluid circulates in a closed loop without an external load or any pump. The findings proved that the pool BHTC of noncovalent nanofluids and DW is less than covalent nanofluids. Furthermore, the functional group added to the graphene surface and functionalization method affected the BHTC, which was in consistent with our results. Also, consistent with the presented results (Figure 11), the noncovalent nanofluids (CNT and GNP nanofluids) showed a smaller increase or lower pool boiling heat transfer than DW. The formation of a thin layer and CNT deposition on the heater surface are the major cause of reduction of HTC. However, GNP deposition on the heater surface increased the nucleation active site.

Figure 12 shows the enhancement of the ratio of nanofluid CHF to the CHF of base fluid (DW) as a function of concentrations. This figure demonstrates that the CHF of all nanofluids studied is higher compared with the base fluid. The CHF of GNP and GNP−PEG nanofluids increases with concentration while the CHF of CNT-based nanofluid decreases with increasing concentrations beyond 0.01 wt %. This implies that the CHF is strongly affected by nanoparticle concentration, nanoparticle type, and functionalization. These observations are consistent with previous results on the CHF for GNP and CNT nanofluids. Enhancement of the CHF is greatest for the GNP nanofluid. The maximum value of CHF for nanofluids was 72% higher in comparison to DW, and a maximum CHF ratio of 1.56 was at 0.1 wt %. GNP−PEG and maximum CHF for CNT- and GNP-based nanofluids were 20% (at 0.01 wt %) and 55% (at 0.1 wt %), respectively. For covalent nanofluids, the increase in the CHF could be attributed to a reduction in heat resistance because no nanoparticle deposition was seen on the surface of the heater.

In Figure 13, the present experimental data for the CHF for different nanofluids versus concentration are compared with the model of Kandlikar. Kandlikar developed a model to estimate the CHF for the saturated pool boiling of pure liquids such as nonhydrodynamic and the hydrodynamic impacts, as well as the orientation of the heater surface. Kandlikar presumed that the onset of CHF is postponed by a dynamic receding contact angle. Figure 13 shows that the measured CHF is consistent with the Kandlikar correlation. The deviation of the experimental data with the Kandlikar equation was on average 15% for CNT nanofluids, 2% for graphene nanofluids, and 7.8% for PEG−graphene nanofluids.

Figure 12. CHF enhancement defined as the ratio of CHF nanofluids compared to CHF basefluid.

Figure 13. Comparison of the measured values of CHF at various concentrations with the predictions of Kandlikar for (a) CNT, (b) GNP, and (c) GNP−PEG nanofluids.
5. CONCLUSIONS

An experimental study on pool boiling heat transfer for pristine and functionalized GNP and raw CNT nanofluids was conducted under atmospheric pressure. Nanofluids were generated by the addition of GNP, functionalized GNP with PEG (GNP–PEG), and CNT to DW. The nanoparticle weight concentrations of 0.01, 0.05, and 0.1 wt % were used in these experiments.

It was found that the CHF and the HTC increased for all nanofluid samples than the DW. With the increase in concentration beyond 0.01 wt %, the HTC of CNT nanofluids decreased, while the HTC of the GNP and GNP–PEG nanofluids increased monotonically with solid concentration. The nanofluid generated by GNP–PEG (0.1 wt %) was the best test sample as it was very stable (over 90 days), and its CHF value and thermal conductivity were the highest of all samples studied and showed, respectively, 72 and 20% enhancement compared to DW. However, the present study showed that the thermal conductivity and functionalization method (noncovalent and covalent) had a direct effect on the HTC and CHF of nanofluids.

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Notes

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