Effect of different surfactants on the pool boiling heat transfer of SiO$_2$/deionized water nanofluid on a copper surface

Sasan Etedali$^{a,b}$, Masoud Afrand$^{a,b,*}$, Ali Abdollahi$^{a,b}$

$^a$ Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
$^b$ Modern Manufacturing Technologies Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran

**ABSTRACT**

The boiling heat transfer is one of the most widely applied heat transfer processes in today’s industries. This study is an experimental investigation of the pool boiling heat transfer in a nanofluid composed of deionized (DI) water and silicon dioxide (SiO$_2$) nanoparticles with added surfactants (Ps$_{20}$, CTAB, SLS) on a copper surface at various nanofluid concentrations, under atmospheric pressure conditions. The nanofluid was synthesized using a two-step method and showed acceptable stability. The concentration of surfactant in nanofluid for all prepared nanofluids is $\frac{1}{20}$ of nanoparticles mass. For the sake of repeatability and accuracy of the experiments, the deionized water was measured three times and was found to match the relations proposed in the literature. The results show the boiling heat transfer to be enhanced in the DI water with added surfactants compared with the deionized water. Moreover, the DI water with added surfactants observed a better boiling heat transfer compared to the DI-water-based SiO$_2$ nanofluid with added surfactant. In addition, the boiling heat transfer was reduced as the concentration of the SiO$_2$ nanofluid containing SLS and CTAB surfactants was increased. Meanwhile, increasing the concentration of the SiO$_2$ nanofluid containing Ps$_{20}$ surfactants from 0.01 to 0.1 vol% enhanced the heat transfer. However, increasing the concentration to 1 vol% reduced the heat transfer drastically. Therefore, at all heat fluxes, the nanofluid specimens with added SLS surfactants were associated with the highest boiling heat transfer, which was followed by the nanofluid with added CTAB, and the nanofluid with Ps$_{20}$ (SLS > CTAB > Ps$_{20}$). In conclusion, ranking them by impact, anionic, cationic, and nonionic surfactants (nonionic < cationic < anionic) resulted in the largest to smallest increase in the Boiling Heat Transfer Coefficient (BHTC) in the nanofluids.

1. Introduction

Cooling systems with many technological advances have encountered a number of constraints, and even with the increasing use of technology, the use of liquid coolers, different geometries of equipment and cooling methods is insufficient for the high volume of heat, hence new methods of increasing heat transfer are required [1–5]. Also for the study the increase in heat transfer for the cooling of equipment, the researchers first should study the single-phase and two-phase heat transfer [6–9]. The boiling heat transfer is one of the most effective and efficient methods of heat transfer in today’s refrigeration and heating industry and different engineering applications. The increased heat-transfer rate in boiling has been attractive to the researchers in this field. Given the large latent heat of the boiling fluid, a large amount of energy is dissipated from the solid surface. This great feature of boiling is utilized in many industrial processes. Different methods of enhancing heat transfer may be classified into active and passive methods. Passive methods include rough surfaces, extended surfaces, and fluid additives while using an electrostatic field, and surface or fluid vibrations are an examples of the activate methods [10–18]. As a passive method, the nanofluids may be used to enhance the pool boiling heat transfer. Nanofluids contain particles below 100 nm that are associated with a higher thermal conductivity compared with the base fluid. Many studies have addressed the boiling of nanofluids [19]. Some researchers have reported an enhancement in heat transfer by using nanofluids [20–22] while others have reported a decrease on heat transfer in nanofluids [23–25]. The boiling heat transfer may be controlled depending on the application, as in some, the goal is to enhance the heat transfer while in some other we seek to reduce it. This has also been addressed by some studies [26–33].

Abdollahi et al. [34] investigated the impact of ferrofluids on the pool boiling heat transfer and deposited surfaces. They used a ferrofluid...
under atmospheric pressure conditions to study the pool boiling heat transfer. By investigating various nanofluid (volume) concentrations, they realized that heat transfer decreases with increasing concentration at high concentrations while being enhanced at low concentrations. Using water/aluminum-oxide nanofluids at concentrations below 1 vol %, Shahmoradi et al. [35] found that the critical heat flux (CHF) is enhanced while the Boiling Heat Transfer Coefficient (BHTC) is reduced in pool boiling over a heating plate. Raell et al. [36] experimentally investigated the performance of the boiling-pool heat transfer and the pressure drop of an aluminum-oxide/water nanofluid in a heat exchanger with turbulent flow. They realized adding nanoparticles enhances the heat transfer. Furthermore, they found the maximum boiling heat transfer taking place at 0.15 vol%. In a study on the boiling heat transfer in a nanofluid composed of ZnO and ethylene glycol, Kole & Dey [37] attained a maximum heat transfer of 40% at a concentration of 3.75 vol%. Moreover, the heat transfer coefficient decreased as the number of ZnO nanoparticles were increased in the nanofluid. This was attributed to the sedimentation of the nanoparticles and the blocking of heating surface.

Silicon dioxide (SiO₂) is the most abundant oxide in the Earth’s crust. Having a favorable specific area and a high BHTC which allows for investigating the heat transfer, and due to their thermal and hydrodynamic characteristics, SiO₂ nanoparticles have attracted much scientific attention. Dadjoo et al. [38] investigated the various inclinations of a copper boiling plate in the SiO₂-water nanofluid. Considering the data, it was found that increasing the inclination of the boiling plate from 0 to 180° enhances the critical heat flux (CHF) but reduces the BHTC. Kulkarni et al. [39] investigated the BHTC of a SiO₂-ethylene glycol (EG) nanofluid. They used SiO₂ nanoparticles of various sizes (20, 50, 100 nm) in their study. They reported the heat transfer coefficient to be increased. Vassallo et al. [40] experimentally investigated the pool boiling heat transfer of a SiO₂-water nanofluid on a NiCr wire heater with a diameter of 0.4 mm. They studied SiO₂ nanoparticles of two sizes (15 and 50 nm), finding the BHTC to be increased with increased nanoparticle size. The incorporation of nanofluids in pool boiling heat transfer has been addressed for a variety of nanoparticles (especially SiO₂) and different base fluids [41–50].

Nonetheless, the impact of different surfactants on the pool-boiling heat transfer has been less addressed [51–55]. Kumar and Milanova [56] compared the impact of surface tension on aCNT-water-surfactant nanofluid to that on a water-surfactant. They examined the sodium dodecylbenzene sulfate (NaDBS) surfactant in various concentrations. Moreover, they reported the surface tension to be smaller in water containing surfactants compared to that in the nanofluid. Wasekar and Manglik [57] investigated pool boiling heat transfer of water with anionic surfactants. This study used sodium dodecyl sulfate (SDS) or sodium lauryl sulfate (SLS) as the anionic surfactant. The boiling heat transfer of water was enhanced considerably with added SDS, however, the enhancement in heat transfer was smaller at higher concentrations. In addition, the enhancement of boiling heat transfer depends on parameters such as the size of the nanoparticles, the shape of bubbles on the heater surface, and the increase in the density of the nucleation sites. Furthermore, dynamic surface tension plays the main role in deforming dynamic bubbles and in heat transfer by adsorption of surfactant molecules during boiling. Wasekar et al. [58,59] experimentally investigated the impact of the anionic and nonionic surfactants on the horizontal cylindrical heater and the pool-boiling heat transfer coefficient. In this study, two anionic surfactants of SDS and sodium lauryl ether sulfate (SLES) and two nonionic surfactants (Triton X-100 and Triton X-305). They show on the impact of the surface tension of surfactants on bubble growth. The anionic surfactants were reported to offer a better enhancement in boiling heat transfer compared to non-ionic ones.

Sarafraz and Hormoz [11] investigated the pool-boiling of aCuO-water nanofluid, using Triton X-100, SDS, and SDS surfactants on a horizontal cylindrical heater. They found the BHTC to be reduced for all concentrations below 4 wt%. This was attributed to the reduced number of nucleation sites and the fact that small cavities could not be filled. Meanwhile, the incorporation of surfactants enhanced the BHTC of the nanofluid which was attributed to the reduced surface tension. Using a ZrO₂-water nanofluid and a flat heating plate, Chopkar et al. [60] observed the heat transfer rate to be reduced as the concentration of the nanoparticles was increased. They claimed the nanoparticles effect on the BHTC to depend on the shape, size, density, and the concentration of the ZrO₂ nanofluid. Moreover, tetramethylammonium hydroxide ((CH₃)₄NOH) was used as the surfactant affecting the boiling heat transfer. Kathiravan et al. [61] investigated the pool boiling heat transfer in multi-walled Carbon Nanotubes (CNTs) in pure water containing 9% anionic SDS surfactants. It was found that the addition of carbon nanotubes drastically enhanced the boiling heat transfer coefficient of the base fluid. Moreover, the BHTC was increased in the CNT-water nanofluid almost two times more than the CNT-water-surfactant nanofluid. They attributed the reduction in the BHTC to the increase in the boiling residues resulted from adding surfactants at high concentrations.

One method that researchers use to stabilize nanoparticles in the base fluid (to prepare a nanofluid) is adding surfactants to the nanofluid. Using surfactants results in a reduction in surface tension and homogenizes the nanofluid by scattering the nanoparticles in the base fluid, leading to an enhanced boiling heat transfer. A survey of previous studies shows that the impact of different types of surfactants (anionic, cationic, and nonionic) on the pool-boiling heat transfer of the SiO₂-water nanofluid is yet to be reported. Therefore, this study is the first to investigate the pool-boiling heat transfer of a SiO₂-DI water nanofluid with three surfactants including cetyl trimethyl ammonium bromide (CTAB), polysorbate 20 (Ps20), and SLS on a flat copper plate under atmospheric pressure conditions. In addition, most previous studies have only presented their observations, therefore, there is a lack of explanation for the heat-transfer behavior of nanofluids with added surfactants. In this regard, this study addresses the impact of surfactants on the BHTC in nanofluids in detail. The question here is whether the addition of surfactants to the nanofluids or ionic structure of them affects the boiling heat-transfer properties of the nanofluid. In better words, which of the nanofluid or the surfactants (anionic, cationic, or nonionic) is more effective on the boiling heat-transfer?

2. Materials and methods

2.1. Preparing the nanofluid

In this study, in order to prepare the nanofluid, a certain amount of SiO₂ nanoparticles (around 6.525 gr SiO₂ nanoparticles for making a 1 vol% SiO₂-DI water nanofluid) was poured into a volumetric balloon where 0.163 gr of the surfactant (CTAB, Ps20, or SLS) was added to it. DI water was then added to the mix, bringing the volume to 250 ml, and the solution was stirred at 500 rpm for 180 min. The solution was sonicated at 60% power with a period of 0.5 s for 20 min at the end. Ultrasonication was carried out in three stages and every sample was sonicated for a total of 1 h. SiO₂ nanoparticles of the same diameter were used in various volume fractions to prepare the nanofluid with water as the base fluid. Nanofluids of various concentrations were prepared by diluting an initial nanofluid using DI water. Equation (1) was used to calculate the amount of base fluid required for making a nanofluid at a specific concentration (vol%).

\[ \phi_1, V_1 = \phi_2, V_2 \]  

(1)

Where \( \phi_1 \) and \( V_1 \) are the volume fraction of the initial (more concentrated) nanofluid and the required volume of the nanofluid to dilute, and \( \phi_2 \) and \( V_2 \) are the volume fraction of the nanofluid and its volume, respectively. To prepare a nanofluid of a specific concentration, the amount of the required nanofluid is found using Eq. (1). The nanofluid is then diluted using the base fluid up to a certain volume. Then,
different concentrations of the nanofluid were prepared by diluting the solution obtained in this step (Table 1). To prepare less concentrated solutions, specific amounts of the initial solution were diluted using DI water according to Table 1. Small volumes picked using a micropipette and discharged them into a 100 ml volumetric flask.

For example, to prepare a 0.5 vol% nanofluid, 75 ml of the 1 vol% nanofluid was taken and brought to 150 ml by adding the base fluid. In this solution, the concentration of SiO₂ nanoparticles is 0.5 vol%. As mentioned earlier, water is used to dilute and prepare the nanofluids according to Table 1. SiO₂-DI water nanofluids containing P20, CTAB, and SLS surfactants were prepared with four concentrations (1, 0.5, 0.1, and 0.01 vol%). It must be mentioned that all materials used in this study were acquired from Merck and Sigma Aldrich. Fig. 1 shows the nanofluid containing SLS surfactants.

### 2.1.1. Investigating the shape of the SiO₂ nanoparticles using TEM

In this study, TEM was employed to characterize the geometry and shape of the nanoparticles. Ethanol was added to the SiO₂ nanoparticles after being diluted down to 0.0001 vol% and 0.1 cc of the solution was placed on a smooth graphite sheet (with asperities of less than 2 nm). After the added ethanol fully evaporated from the graphite surface, TEM was carried out and the heights of the nanoparticles were measured. The shape, geometry, and the diameter of the nanoparticles were specified using the low-height areas (graphite surface) and the asperities formed by the nanoparticles considering the TEM scale (Fig. 2). The synthesized nanoparticles were found to be almost spherical. Moreover, the diagrams show the size of the SiO₂ nanoparticles to be around 50 nm.

### 2.1.2. X-ray diffraction (XRD)

XRD is a test used to prove and characterize the type of nanoparticles in the nanofluid used in the experiment. The XRD results for the SiO₂ nanoparticles are presented in Fig. 3. As evident from the results, a peak can be found at 25° which suggests the SiO₂ nanoparticles have a non-crystalline structure. The crystal grain size in the nanoparticle samples may be estimated with the help of the related

<table>
<thead>
<tr>
<th>The concentration of nanoparticles in the base fluid (volume fraction)</th>
<th>Volume (ml) picked from the 1 vol% nanofluid</th>
<th>The final volume after dilution</th>
</tr>
</thead>
<tbody>
<tr>
<td>%1</td>
<td>–</td>
<td>150</td>
</tr>
<tr>
<td>%0.5</td>
<td>75</td>
<td>150</td>
</tr>
<tr>
<td>%0.1</td>
<td>15</td>
<td>150</td>
</tr>
<tr>
<td>%0.01</td>
<td>1.5</td>
<td>150</td>
</tr>
</tbody>
</table>

Fig. 1. SiO₂-DI water nanofluids containing 50 nm SLS surfactants in four concentrations (1, 0.5, 0.1, and 0.01 vol%).

Fig. 2. TEM results for SiO₂ nanoparticles at a magnification of 40 nm.

Fig. 3. XRD results for SiO₂ nanoparticles.
relations and the XRD results. Moreover, a comparison between this diagram and the results reported in previous studies shows that SiO₂ nanoparticles are very pure and can be assumed to only have an O–Si–O structure. XRD also shows that these nanoparticles are irregular (amorphous) and have no crystalline network (the middle peak). Meanwhile, the peak is similar to the other silica nanoparticles, which shows that this is a pure silica nanoparticle.

2.1.3. Dynamic Light Scattering (DLS)

As it was mentioned in previous studies, one way for measuring the size of nanoparticles in a base fluid is through DLS. In this study, DLS was employed to measure the size of the SiO₂ nanoparticles in the base fluid (DI water) and to prepare nanoparticle size distribution diagrams. The results for the measurement of the diameter of the nanoparticles is presented in Fig. 4 for the nanofluid. Given the fact that this test method works by the dynamic scattering of the light, a nanofluid with a concentration of 0.01 vol% (the lowest possible concentration) was used to prevent particles interfering with one another and resulting in deviation and error in the measurement. Moreover, DLS tests lasted for 10 min after the nanofluid samples were prepared by sonication. The DLS results for the water-SiO₂ nanofluid is suggestive the average diameter of the nanoparticles in the base fluid after ultrasonication to be 48.63 nm which is in agreement with TEM results.

2.1.4. Nanoparticle stability test results (Zeta potential)

A suitable criterion for investigating the stability of the SiO₂ nanoparticles in the DI water and to verify that particle agglomeration does not take place is the surface charge of the nanoparticles which results in electrostatic repulsive force between them. Surface charges prevent the agglomeration of the nanoparticles. Thus, the higher the surface charge of the nanoparticles (positive or negative) the more stable the nanofluid as nanoparticle agglomeration will be prevented more efficiently. In this study, the Zeta potential test was employed to investigate the stability of the SiO₂ nanoparticles in the base fluid. In this test, the maximum surface charge of the SiO₂ nanoparticles was found to be either below −40 mV or above +40 mV in all nanofluids (DI water-SiO₂ nanofluids containing SLS, CTAB, and Ps20 surfactants) which, considering the nature of the nanoparticles and the base fluid, means that the nanofluid is stable [62]. The results of the Zeta potential test are presented in Fig. 5 through 7 for the DI water-SiO₂ nanofluids containing SLS, CTAB, and Ps20 surfactants, 30 min after they were prepared and sonicated. The Zeta-potential diagrams show all surfactants to provide excellent nanofluid stability. Due to the stability of the nanoparticles in the base fluid, the agglomeration of the nanoparticles and its effect on the physical properties such as the thermal conductivity of the nanofluid, nanofluid viscosity, and the specific heat can be ignored. The results of the Zeta-potential test in Figs. 5–7 show the maximum surface charge for the nanofluids with SLS, CTAB, and Ps20 surfactants to be −87.4, 74.2, and −97.9, respectively, all of which satisfy the stability conditions. It is thus concluded that the oxide nanoparticles used in study are stable and are sufficiently charged to prevent their agglomeration (nanofluid stability means that nanoparticle agglomeration and sedimentation do not take place).

2.2. Experimental apparatus

The boiling heat transfer apparatus used in this study was composed of four main parts: the glass boiling chamber, the copper cylinder, the electronic power control unit, and the cooling system. Figs. 8 and 9 show a schematic view of the apparatus.

The main boiling chamber was a German-made quartz cylinder with high thermal resistance (up to 1600 °C). The 350 mm long glass chamber has an inner diameter of 40 mm and a thickness of 3 mm. The glass cylinder was made with an edge at the bottom that served for sealing. Using a silicone gasket, the glass tube was placed on it concentrically with respect to the copper block. In order to create one-dimensional heat transfer conditions, the copper must be surrounded by a material with low thermal conductivity compared to copper so to concentrate the heat flux in the vertical direction to the top. In this regard, an Italian-made, high-grade, Polytetrafluoroethylene (PTFE) cylinder was used that was 150 mm wide and 90 mm tall. The heat transfer coefficient was measured using a Decagon KD2 Pro thermometer (with an accuracy of 0.01) and was found to be 0.29 w/mK. In addition, the PTFE was threaded to the size of the outer diameter of the copper block to be placed inside the PTFE. Two 3 mm holes were drilled into the Teflon casing to place the sensors at 90° with respect to one another (Fig. 10). The copper block was shaped like a 90 mm long and 40 mm wide cylinder and was made of 96% pure copper (Fig. 10). Using a British Cousins P5687 apparatus, the thermal conductivity of copper was measured to be 401 w/mK. Considering the fact that the thermal conductivity of copper is many times larger than that of PTFE, heat transfer in the radial direction was successfully minimized. Four vertical, 6 mm wide and 40 mm long holes were embedded at the end of the copper cylinder to secure the heating elements (Fig. 10). Four 6 mm wide and 4 cm long, 250 W, steel heating elements were placed at the end of the copper block. It is important to note that all of the heating elements were completely located inside the copper block and had no contact with air. Moreover, two holes were drilled 20 mm into the
copper block (to the center), 15 mm and 38 mm away from the top of the cylinder at 90° with respect to one another. These holes served to place the PT-100 sensors. Note that the whole outer surface of the copper block is threaded so it can be placed inside the PTFE (Fig. 10). The diameter of the glass chamber matched that of the copper block. It must be kept in mind that the glass chamber is brittle and cannot withstand a large pressure. Therefore, to seal the device, a stainless steel holder with a diameter of 45 mm was used that had three holes 120° apart from one another to be riveted to the Teflon. The holes reach back to the end of the Teflon piece where a threaded pin is connected to them. It must be noted that before connecting the glass, a silicone gasket (with an inner diameter of 38 mm and an outer diameter of 65 mm) was placed on the copper block. Moreover, the holder was attached to the screws using a polyurethane gasket after the glass chamber was put in place. This gasket allows for applying more pressure to the glass without breaking it. The holder screws were selected from the M16 size and were 10 mm long. The space between the heater and heating block is perfectly filled with silicone adhesive (approximately between 0.1 mm) with an estimate of the volume (distance) between the heater and heating block and silicone adhesive and additional adhesive out of space between them we ensure that the space between the heater and thermal block has been filled with adhesive. After using silicone adhesive, the space between the thermal block and surrounding air is completely covered with insulating stone adhesive. This will cause minimizing the heat loss. Similarly we used silicone adhesive for holes where there is a thermocouple as before (the space between the heater and heating block) and to ensure the layer of suitable insulating stone adhesive and fiberglass around PTFE. The reason for using silicon adhesive is due to its high thermal conductivity coefficient. Also the main application of this adhesive is for computing processors such as CPUs and etc.

In this study, 30 cm long PT-100 resistive temperature detectors (RTD) with an accuracy of 0.1 K were used. The sensors were calibrated to the temperature measurement range. Two Autonics TC4Y temperature displays were also used. With an error of only 0.1, the 4-character displays were very accurate. They also allowed for adjusting the temperature so the contactor could be directly commanded to connect/disconnect the elements for device safety. In addition, the dimensions of the electrical enclosure were 35 in 40 cm. The ammeter andvoltmeter used in this study were both products of Micromax.

Given the fact that a uniform heat flux is required for accurate test conditions, an auto transformer device was required for maintaining the voltage and the current. The single-phase auto transformer attached to the device was a product of Goldstar and provided an output voltage of 0–300 V. The manually adjustable auto transformer worked with AC voltage and was directly connected to the mains. A cooling system was embedded into the boiling chamber to maintain the surface of the fluid and prevent its evaporation. The system was composed of a 200 mm long glass condenser that was connected to the glass chamber with a 40 mm polyurethane gasket. In addition, after the condenser was placed on the glass chamber using the gasket, a special glue was used to ensure the device is perfectly sealed. The cooling system is separate from the device. The pump inside the cooling vessel sends ice water into the condenser by passing through the rotameter which condenses the vapors. The condensed vapor then returns to the boiling chamber and water circulates back to the cooling vessel again. Furthermore, the bottom side of the heating elements was perfectly insulated using glass wool to prevent energy dissipation. The condenser chamber was open to the atmosphere, therefore, the boiling chamber was at atmospheric pressure. Comparing the input power and the increase in the energy of

![Fig. 5. Zeta-Potential test results for SiO2 nanoparticles with added SLS surfactants with a concentration of 0.01 vol% in DI water as the base fluid.](image1)

![Fig. 6. Zeta-Potential test results for SiO2 nanoparticles with added CTAB surfactants with a concentration of 0.01 vol% in water as the base fluid.](image2)
the cooling system energy dissipation is less than 10% under the operational conditions. Surface roughness was measured using a Mitutoyo (U.S.A) SJ210 surface roughness tester. The standard uncertainty of surface-roughness measurement is around 10%. The roughness diagram is presented in Fig. 11. It is evident that surface roughness was constant (0.319 μm or 319 nm) at the start of every experiment. To ensure the surface roughness is similar at the start of every experiment, the copper was polished with a sandpaper P600.

2.3. Measurement

To obtain the boiling curves, the boiling surface temperature (T_s) and the fluid saturation temperature must be known and the heat flux (q″) applied to the fluid must be calculated. Now, reading the temperature directly from the sensor on the surface is associated with a considerable error which is due to the additional nucleation site. In this study, the boiling surface temperature was measured indirectly through extrapolation. According to Fig. 12, two holes were embedded into the copper block 15 and 38 mm away from the top side of the copper cylinder, 120° apart. 150 cc of either 0.01, 0.1, 0.5 or 1 vol% nano fluid was charged into the boiling chamber for each experiment. Then, the nano fluid was heated at pre-specified voltages and currents. To maintain a constant heat flux and ensure the stability of the system, the temperature was recorded every 10 min (\( \frac{dT}{dt} = 0.01 \frac{K}{min} \)).

As discussed earlier, given the fact that the thermal conductivity of copper is much higher than that of PTFE, the temperature gradient in the radial direction can be ignored and the heat transfer may be assumed one-dimensional. The heat flux transported to the boiling surface is calculated as follows:

\[
q'' = K \frac{T_2 - T_1}{d_2 - d_1}
\]

(2)

The heat flux may be obtained using Eq. (2): After the heat flux was determined, the difference between the temperature of the boiling surface and the saturation temperature can be determined using Eq. (3).

\[
\Delta T_s = T_s - T_{sat} = \left( T_1 - \frac{q'' d_1}{K} \right) - T_{sat}
\]

(3)

The BHTC was then calculated from the heat flux and the superheat temperature of the wall according to Eq. (4):

\[
h = \frac{q''}{\Delta T_s}
\]

(4)
3. Results and discussion

3.1. Boiling curve and repeatability

To ensure the accuracy of measurement, first, the DI water was tested three times and was compared to the Rohsenow's Curve. The experimental relation that was proposed by Rohsenow may be expressed as follows [63–65]:

$$\Delta T_s = \frac{h_f g C_p}{h_{fg}} C_{sf} q^* \left( \frac{\sigma}{g (\rho_1 - \rho_2)} \right) ^{0.5} \left( \frac{\rho_1}{\rho_2} \right) ^{0.5} Pr^n$$

Fig. 9. The schematic view of the apparatus.

Fig. 10. View of the copper cylinder.
researchers have measured the temperature directly and there have been a large of numbers of studies where the surface temperature was measured by extrapolation [19,20,32–34,38,63].

The uncertainty analysis based on the method proposed by Moffat [66] was carried out according to Eqs. (6)–(8).

\[
\frac{U_{q'}}{q'} = \left[ \left( \frac{U_{q'-T_s}}{T_s - T_l} \right)^2 + \left( \frac{U_{d_2-d_1}}{d_2 - d_1} \right)^2 \right]^{\frac{1}{2}}
\]

(6)

\[
\frac{U_{\Delta T_s}}{\Delta T_s} = \left[ \left( \frac{U_{T_s-T_{sat}}}{T_s - T_{sat}} \right)^2 + \left( \frac{U_{\Delta T_s}}{\Delta T_s} \right)^2 \right]^{\frac{1}{2}}
\]

(7)

\[
\frac{U_h}{h} = \left[ \left( \frac{U_{\Delta T_s}}{\Delta T_s} \right)^2 + \left( \frac{U_{q'}}{q'} \right)^2 \right]^{\frac{1}{2}}
\]

(8)

The uncertainty for measurement of temperature is 0.1 K and 0.1 mm for the measurement of lengths. Also standard uncertainty for measuring surface roughness is about 10%. The results are suggestive the largest uncertainty in the calculation of the heat flux and the BHTC to be 6.5 and 8.4%. The heat flux is plotted in Fig. 13 against the wall superheat for the DI water. The heat transfer diagrams were identical after the experiments were repeated for three times in different days. This means that the results will remain in this range regardless of how many times the experiments are repeated.

Fig. 11. Testing the roughness with a SJ 210 surface roughness tester (Ra = 0.319 μm).

Fig. 12. Arrangement of PT-100 resistive sensors.

Fig. 13. The heat flux with respect to the wall superheat in the DI water compared to the Rohsenow’s correlation.

Fig. 14. Arrangement of PT-100 resistive sensors.
3.2. The boiling curve of DI water-surfactant

The heat flux is plotted Fig. 14 against the wall superheat in DI water compared to the DI water-SLS surfactants. As evident from the figure, the results show that the diagram of the heat transfer coefficient of the DI water-surfactant is shifted to the left. Therefore, the BHTC for the DI water-surfactant solution is higher compared to the DI water for all heat fluxes. Adding surfactants has reduced the surface tension which facilitates the separation of the bubbles from the surface, enhancing the heat transfer. Fig. 14 shows the boiling diagram for the specimen with added SLS surfactants, the diagram corresponding to specimens with Ps20 and CTAB are also similar. This means that for all heat fluxes, the heat transfer coefficient for the specimens with DI water and a surfactant is larger than that of DI water. To avoid redundancy, only the diagram corresponding to SLS is shown here. Moreover, it is evident that as the heat flux is increased and boiling continues in the nucleate boiling region, the BHTC is increased to a larger extent which is probably due to the acceleration of the separation of bubbles from the surface and the increased number of nucleation sites in the nucleate boiling region.

3.3. The boiling curve of SiO2– DI water nanofluid with SLS surfactant

Fig. 15 shows the boiling curve for the SiO2-water nanofluid containing SLS surfactants at four nanoparticle volume fractions (0.01, 0.1, 0.5, and 1 vol%) compared with DI water and DI water-surfactant specimens. As mentioned earlier, the incorporation of surfactants enhances heat transfer. The enhancement in the heat transfer is due to the nature of surfactants that reduce the fluid surface tension, facilitating the separation of bubbles from the surface and enhancing the heat transfer. Therefore, according to Fig. 15 which shows the variations in the heat flux with respect to the wall superheat, the heat transfer of DI water-surfactant is increased compared with DI water. Moreover, it is observed that increasing the concentration of the nanofluid (especially up to 0.5 and 1 vol%) reduces the heat transfer due to increased sediment. Sediment on the boiling surface at high heat fluxes increases the thermal resistance and reduces the heat transfer. In addition, the capacity of the surfactants (for reducing surface tension) is reduced at higher heat fluxes in comparison with the increase in the concentration of the nanoparticles for changing the heat transfer. Therefore, as the concentration of the nanoparticles is increased, the density of

3.4. The boiling curve of SiO2– DI water nanofluid with CTAB surfactant

Fig. 16 shows the boiling curve for the SiO2-water nanofluid containing CTAB surfactants at four nanoparticle volume fractions (0.01, 0.1, 0.5, and 1 vol%) compared with DI water and DI water-surfactant specimens. Similar to what was mentioned earlier, the incorporation of CTAB also reduces the surface tension and enhances heat transfer. Reduced surface tension means the bubbles are separated from the surface more easily, thus enhancing the heat transfer. Therefore, according to Fig. 16, the boiling heat transfer in DI water-CTAB solution is enhanced.
compared with DI water. It is evident from the figure that, similar to the case with SLS, as the volume concentration of the nanofluid is increased, heat transfer is reduced as a result of the sediment, especially at 0.5 and 1 vol% concentrations. The thermal resistance of the surface is increased by sediment on the boiling surface at higher heat fluxes, reducing the heat transfer. Similar to the case with SLS, it is evident that at higher heat fluxes and concentrations, the capacity of the surfactant (in reducing the surface tension) for overcoming the effect of the increased nanoparticle concentration is reduced, which results in fewer nucleation sites, and thus, reduced heat transfer.

3.5. The boiling curve of SiO$_2$ DI water nanofluid with Ps20 surfactant

The main application of Ps20 is in the food and cosmetics industry as an additive. Also one of the advantages of using it is the non-toxicity of this substance, which can be used in various cases, especially under sensitive and hazardous conditions. Fig. 17 shows the boiling curve for the SiO$_2$-water nanofluid containing Ps20 surfactants at four nanoparticle volume fractions (0.01, 0.1, 0.5, and 1 vol%) compared with DI water and DI water-surfactant specimens. Similar to previous discussions, the incorporation of Ps20 also reduces the surface tension and enhances heat transfer. Reduced surface tension means the bubbles are separated from the surface more easily, thus enhancing the heat transfer. Therefore, according to Fig. 17, the boiling heat transfer in DI water-Ps20 solution is enhanced compared with DI water. According to Fig. 17, it is evident that the heat transfer coefficient was increased with the concentration increasing from 0.01 up to 0.1 vol%, However increasing the concentration to 1 vol% reduced the heat transfer drastically. The heat transfer is enhanced as the concentration is increased from 0.01 to 0.1 vol% as a result of the dominance of the impact of Ps20 which reduces the surface tension of the nanofluid. However, when the concentration was increased up to 1 vol%, the reduction in the surface tension caused by the surfactant became less significant compared to the increase in the concentration of the nanoparticles, sediment was increased, the number of nucleation sites was reduced, and the surface resistance was increased, thus reducing the heat transfer. Given that Ps20 surfactant is a non-ionic surfactant, it cannot help the stability of nanofluids than other surfactants, so it can bond nanoparticles and precipitation more than other surfactants on the surface, thereby reducing BHTC. Another reason may be that Ps20 surfactant has a very long chain that causes the long chain adheres to the surface and causes more adhesion and precipitation on the surface, thereby reducing BHTC.

3.6. Comparing the boiling curve the SiO$_2$ Water nanofluid with different surfactants

In order to investigate the impact of different anionic, cationic, and nonionic surfactants on the BHTC of the SiO$_2$-DI water nanofluid, three surfactants were used (SLS, CTAB, and Ps20). Fig. 18 shows the boiling heat transfer curve for the DI-water-based SiO$_2$ nanofluid with Ps20, CTAB, and SLS surfactants. As evident from the figure, at all heat fluxes, the nanofluid specimens with added SLS surfactants were associated with the highest boiling heat transfer, which was followed by the nanofluid with added CTAB, and the nanofluid with Ps20. Therefore, it is safe to say that nonionic, cationic, and anionic surfactants have the largest to smallest impact on the boiling heat transfer of the nanofluids. This is also in agreement with the findings of previous studies [67]. Ultimately, ranking them by their impact on the heat transfer of the SiO$_2$-DI water nanofluid, SLS surfactants, followed by CTAB, and then Ps20 were the most to least effective surfactants to enhance the heat transfer (SLS > CTAB > Ps20).

4. Conclusion

This study is an experimental investigation of the pool-boiling heat transfer in a nanofluid composed of deionized (DI) water and silicon dioxide (SiO$_2$) in with added anionic, cationic, and nonionic surfactants (SLS, CTAB, Ps20) at various nanofluid concentrations and under atmospheric pressure conditions. The nanofluid was synthesized using a two-step method and showed acceptable stability. The presence of the surfactants in the nanofluid reduces the surface tension, thus enhancing the Boiling Heat Transfer Coefficient (BHTC) through facilitating the separation of the bubbles from the boiling surface. The results of this study may be summarized as follows:

- The incorporation of surfactants increases the heat transfer coefficient. In addition, at higher heat fluxes and concentrations, heat transfer is reduced.
- The BHTCs of the specimens composed of DI water and any of the
surfactants were higher than that of the DI water.

- The BHTCs of the specimens composed of DI water and any of the surfactants were also higher than that of the SiO$_2$-DI water-surfactant nanofluid.

- The BHTC is reduced by increasing the concentration of the SiO$_2$ nanofluids containing SLS and CTAB surfactants.

- In the specimen with the Ps20 surfactant, the heat transfer coefficient increased with the concentration increasing from 0.01 up to 0.1 vol%, However increasing the concentration to 1 vol% reduced the heat transfer drastically.

- This study is the first to use the nonionic Ps20 surfactant to stabilize the SiO$_2$-DI water nanofluid for measuring its BHTC.

- At all heat fluxes, the nanofluid specimens with added SLS surfactants were associated with the highest boiling heat transfer, which was followed by the nanofluid with added CTAB, and the nanofluid with Ps20 (SLS > CTAB > PS20).

- It can be thus concluded that anionic, cationic, and nonionic surfactants (nonionic < cationic < anionic) resulted in the largest to smallest increase in the BHTC of the nanofluids.

References


