Experimental investigation of the effect of one dimensional roughened surface in the pool boiling of nanofluids

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Abstract
The objectives of this research are to develop a special surface for increasing the nucleation heat transfer characteristics, decreasing the superheat temperature and postponing the occurrence of critical heat flux for long term work. A laboratory apparatus was built. In order to more feeding the microlayer of the bubble by capillary force of the micro-grooves, the boiling surface was roughened in one direction. Despite the fact that the boiling characteristics of roughened surface are improved relative to the polished surface, the results are not very impressive. Although the boiling of two Nano-fluids, copper oxide and alumina on the micro-groove surface resulted in a significant increase in the nucleation heat transfer but this method cannot be used for a long time process because of the continues deposition of nanoparticles over the time and creation of insulation layer on the micro-groove surface. Therefore, simultaneous utilization of micro- groove surface, as well as the depositing of a thin and porous layer of nanoparticles on the surface increased the feeding of sites and the production of bubbles respectively. The critical heat flux and boiling heat transfer coefficient for the surface deposited with copper oxide nanoparticles enhanced by 46.5% and up to 74.2% respectively.

Key words: Pool boiling, One dimensional roughened surface, Deposition of nanoparticles, Critical heat flux, Heat transfer coefficient

1. Introduction
Electrical systems and equipment are sensitive to heat. The development of material science and manufacturing technology has attracted the attention of many researchers to reduce the equipment size. Shrinking the size of the parts has brought the electronics parts closer to each other. Therefore, the use of single-phase heat transfer techniques, such as usage of fins and blowing the air with fan through the fins, cannot control the hot spots on the surface and eliminate extreme thermal gradients, which can damage sensitive parts. One of the best ways to meet this demand is to use a two-phase heat transfer technique. The two-phase boiling process can transfer heavy heat loads from a limited surface, and also in a very low temperature difference between the surface and the fluid, due to the absorption of the latent heat of evaporation from the surface during the production of bubbles. Conversely, when the received heat flux surpasses the critical heat flux (CHF), the steam completely covers the surface and the surface temperature rises sharply due to less steam conductivity than the base fluid. Finally, the boiling heat transfer characteristics are severely diminished.

The concept of boiling and recognizing nucleate boiling regions was introduced by Nukiyama in the 1934 [1]. Researchers who are aware of this process, tried to reduce the superheat temperature of the surface and also increase the heat flux and heat transfer coefficient simultaneously. Various effective parameters are available to improve the boiling heat transfer characteristics of fluids in low, medium and high heat fluxes. Early onset of nucleation in low heat fluxes, increasing the number of active nucleation sites and hydrophilicity of the surface in medium heat fluxes, and postponing the event of critical heat flux and tearing of insulating bubbles formed on the surface in high heat fluxes are the most important factors [2]. Pournaderi et al [3], investigated the simulation of the oblique collision of a water droplet on a superheated surface via a novel algorithm. The high temperature of the surface leads to the formation of a vapor layer between the droplet and surface. In this method, mesh clustering near the surface is used to capture the effect of the vapor layer. Available experiments confirmed the validity of the proposed algorithm. The results showed that the Weber number depends on the average speed of the collision of the water droplet, and also the drop radius and the contact time of the droplet depend on the normal weber number. Nawaz et al [4], studied the hydrothermal

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characteristics of the Al₂O₃ and CuO nanofluids subjected to Brownian motion by finite element method (FEM). They used KKI model for effective thermal conductivity and viscosity. They found that dispersion of nanoparticles in the pure fluid increase the thermal conductivity of the resulting mixture. They also observed that effective thermal conductivity of Al₂O₃ nano- liquid is greater than of CuO nano-liquid. Convection at the surface plays a notable effect on the temperature of nano- liquids. Heat generation in CuO liquid is less than the heat generation in Al₂O₃ near the vicinity of the wall. However, away from the wall, opposite trends are observed. This study also recommends that the nanofluids are the best coolant as compare to the base fluids.

Roughening the surface with sandpaper or machining is one of the simplest ways to improve boiling heat transfer characteristics which may increase heat transfer coefficient [5, 6, 7]. Typically, heat transfer media are composed of fluids such as water, ethylene glycol or oil, which has much lower heat transfer coefficient in comparison with metals and even metal oxides. Therefore, it is expected that fluids containing very small particles of these compounds show better thermal properties than pure one. The idea of nano-fluids was introduced by choi in 1995 and led to a massive revolution in the field of heat transfer of fluids [8]. Boiling of nanoparticles resulted in modification of viscosity, surface tension, thermal conductivity and thermo-physical properties of the suspended particles and particles deposition on the surface brought about a change in hydrophilicity, roughness and active nucleation sites of the surface. When the size of the nanoparticles becomes larger, the weighting effect overcomes the diffusion and then the nanoparticles are deposited. Not only depositing nanoparticles whose size exceeds the average roughness of the surface on the cavities reduces the density of active nucleation sites and varies the surface roughness, but also it increases the wettability and nutrition of nucleation sites [9].

Wen and Ding [10] performed a pool boiling test using a water-alumina nano-fluid, under atmospheric conditions. The results indicate that heat transfer is noticeably improved by increasing concentration of nanoparticles. Putra et al. [11], used copper oxide and water-alumina nano-fluids to investigate natural convection heat transfer of pool boiling. The results showed that the depositing of nanoparticles on the surface would increase the wettability of the surface and also increase the thermal resistance of the surface and reduce the heat transfer from the hot surface to the cooling fluid. Therefore, the higher concentration of nanoparticles causes the lower heat transfer coefficient. As can be seen in Table 1, many researchers have studied pool boiling of various nano-fluids and presented conflicting results.

Despite execution of several experiments by the researchers about pool boiling of nano-fluids and deposited surfaces, it seems that no one has ever considered the combination of depositing nanoparticles, one direction roughened surfaces and surfaces porosity. Based on contradictory findings from previous studies, in this study, the pool boiling test is performed to clarify the effects of deposition, material and size of nanoparticles on heat transfer coefficient and critical heat flux.

In this study, initially, the boiling test was performed using a roughened surface in one direction as well as a Deionized water fluid under saturation temperature, atmospheric pressure and ambient temperature of 23°C, then the extracted results were tested for uncertainty analysis. Alumina (alpha series) and copper oxide nanoparticles with average particle size of 30nm and 10nm, and identical 0.1% vol. Concentrations were stabilized using a magnetic stirrer and ultrasonic process. Using this two-step method, without using a surfactant, leads to stability of nanoparticles up to 168 hours. A pool boiling test was conducted in the presence of two nano-fluids on one direction roughened surface. The surface was deposited from low to high heat flux by nanoparticles slowly. Since the presence and boiling of nano- fluids cannot be considered as a desirable long-term stability method, after creating a porous layer with appropriate thickness and strength, the nano-fluids is drained out of its boiling chamber and its boiling test in the presence of two deposition levels and DI water was performed. Finally, all the extracted results were compared with each other and the best and most enduring state was reported.

2. Setup of pool boiling apparatus

The image of the boiling apparatus is shown in Figures 1 and 2. The boiling chamber of this device is made up of a cylindrical borosilicate glass with dimensions of 300×200×5mm which is highly resistant to high thermal stresses. On the other hand, this cylinder is completely transparent and provides conditions for taking pictures of its boiling. This Pyrex chamber is connected to two stainless steel plates by silicone O-ring from top and bottom while it is completely sealed by Room Temperature Vulcanizing (RTV) silicone adhesive sealant. In order to keep the volume and concentration of the nano-fluid constant, a copper spiral condenser has been used to condense the vapor generated by boiling inside the boiling chamber. The condenser is connected by a hose to water pump, which is located inside a reservoir of cool fluid that formed a closed
condensation cycle. A pressure gauge is used to control the pressure inside the boiling chamber, and a safety valve have been used to restore the inside pressure of the reservoir through the discharge of excess steam into the environment. Also, to control the temperature and keep the boiling fluid in saturation conditions, a thermostat connected to the sensor and a water heater is used. The heater cartridge, which is manufactured by Computer Numerical Control (CNC) machining process with a thickness of 40 mm, height of 250 mm and 23 mm boiling surface diameter, is made of copper for its high thermal conductivity. Four RTD-Pt100 resistance sensors with a precision of ± 0.1 °C, thickness of 5 mm and length of 11.5 mm were installed on the cartridge after being calibrated in a constant temperature bath. To achieve better heat transfer between the cartridge body and sensors, the silicon silver paste with thermal conductivity of 4.5 W/m°K has been used. In order to exclude radial heat transfer from the cartridge to the environment, the heater cartridge was completely covered by a combination of thermal insulation such as fiberglass, wool and Poly Tetra Fluoro Ethylene (PTFE) insulation. The cartridge was finally connected to a 1500W heater. Likewise, by using a 3000 Watt Ototrans, which is connected to a multimeter, the power of the heater increases gradually. The extracted data from the Resistance Temperature Detector (RTD) sensors is transferred to a Data Acquisition system (DAQ) and categorized by means of a computer. Additionally, for taking pictures of different regions of boiling, the LED lamp and a high frame-rate camera are used.

3. Results

The study consists of six experiments, a polished and one dimensional roughness surfaces, the one dimensional roughness surfaces in the presence of nanofluids, the one dimensional roughness surfaces deposition by the nanoparticles. Surface morphology scanning and hydrophilic test for all surfaces and particles diffusion test has been performed.

3.1. Boiling test on clean surface

After machining the boiling surface, the copper surface perfectly roughened by a 600-grit sandpaper in one direction while an average roughness was 0.114μm. In order to remove fats and contaminations from the surface, the boiling surface was completely cleaned with linen acetone-impregnated tissue. Performing the boiling test on the smooth and roughened surface in the presence of DI water as a working fluid, the Figures 3 and 4 were obtained and the results were compared with each other. The surface morphology analysis using the Scan Electron Microscope (SEM) images in the Figure 5- case A, confirms that the motion of the sandpaper has been entirely in one direction, but the roughened surface has few nucleation sites and porosity. Subsequently, the amount of wettability of the boiling surface was measured by using the droplet static contact angle with the surface. According to Figure 6-case A, the results represented that due to low surface porosity and capillarity, the drop had a slight tendency to extend on the surface and contact angle was approximately 75°. Hence, lower nucleation sites are fed by fluid. This problem was partly resolved by creating parallel microgrooves on the surface that could, by their own capillary force, bring nearby fluid underneath the bubble microlayer. In a lower temperature difference relative to the polished surface, the critical heat flux and heat transfer coefficient reached 1095 kW/m² and 62 kW/m²°K respectively. A few nucleation sites are active and produce bubbles in low heat fluxes. Moreover, the geometric shape of the cavities caused the bubbles not to be exited from the sites as jet so that they often collide and merge with each other on the boiling surface and produce large bubbles which is visible in Figure 7 - clean surface.

3.2. Data extraction method and uncertainty analysis

Since the heater cartridge is completely covered by a combination of thermal insulation, radial heat transfer can be ignored. In other words, heat transfer should be considered as one dimensional and in axial direction. In Figure 2, the position of the sensors inside the cartridge is displayed. By fitting the internal temperatures of the heater cartridge in different heat fluxes in the Figure 8, it was found that curves deviation in all heat fluxes is close to 1. That is why the temperature distribution function can be assumed to be linear. The heat flux can be calculated using the Fourier one-dimensional heat transfer relationship.

\[ q^* = -k \frac{\partial T}{\partial Z} \]  \hspace{1cm} (1)

The value of the heat flux calculated by equation 1 was assumed to be constant. Therefore, the boiling surface temperature can be estimated using expansion of Fourier's law between sensor 1 and boiling surface.
Calculating the boiling surface temperature from equation 2 and measuring the boiling fluid temperature by sensor 5, the heat transfer coefficient also would be calculated using the Newton's law of cooling equation 3.

\[ \Delta T = T_s - T_{sat} \]

\[ h = \frac{Q}{A \Delta T} \]  

Errors are the main factors causing the difference between calculated values and the actual values. Human factors or lack of calibration of equipment and parts cause errors. Applying the Holman method, error propagation (Relation 4) and uncertainty analysis was implemented [12].

\[ U = \left[ \sum_{i=1}^{j} \left( \frac{\partial r}{\partial X_i} \right)^2 U_i^2 \right]^{1/2} \]  

\[ \frac{U_{q^*}}{q^*} = \sqrt{\left( \frac{U_{T_1-T_s}}{T_1 - T_s} \right)^2 + \left( \frac{U_{Z_{1}}}{Z_{1}} \right)^2} \]  

\[ \frac{U_{\Delta T_s}}{\Delta T_s} = \sqrt{\left( \frac{U_{T_1-T_{sat}}}{T_1 - T_{sat}} \right)^2 + \left( \frac{U_{Z_{s}}}{Z_{s}} \right)^2} \]  

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

Based on the accuracy of the measuring device and using the Holman method from expanded relationships 5 to 7, the maximum calculation error of heat flux and heat transfer coefficient is calculated 6.3% and 9%, respectively. Slight distance of thermocouples from each other, as well as low temperature differences, increase uncertainty. Increasing the heat flux causes an increase in the temperature difference, and hence the uncertainty percentage decreases (Figure 9). In heat fluxes greater than 500kW/m², the uncertainty percentage associated with the calculation of heat flux and heat transfer coefficient are reduced to less than 1.4% and 2.81% respectively.

3.3. One-directional roughened surface in the presence of Nano-fluids

Copper oxide and alumina nanoparticles are used to improve the heat capacity of the base fluid as well as overcoming the problem of porosity deficiency on the surface. By the same token, 3 liters of 0.1% vol. nano-fluids are produced from both nanoparticles. No surfactants or other reactants were used to stabilize the nano-fluid because utility of these additives caused several problems, such as reducing the effective particle surface during the heat transfer, instability at high temperatures and the production of foam, which would be able to weaken the heat transfer process [13]. In order to eliminate nanoparticles adhesion to each other and to achieve uniform nanoparticles distribution in the base fluid, the nano-fluid was initially blended with magnetic stirrer for 4 hours and then exposed to ultrasonic waves for 3 hours. Finally, the mentioned nano-fluid remained at stable condition for a week. To verify the purity and quality of purchased particles, both nanoparticles were tested X-ray Diffraction (XRD) in Figure 10. The X-ray diffraction pattern of nanoparticles illustrates that the pattern matching with other particle-diffusion images. The Transmission electron microscopy (TEM) test demonstrated that alumina and copper oxide nanoparticles have a nearly spherical geometry, while their average diameter is 32 nm and 10 nm, respectively. In the presence of nanoparticles, Pool boiling test was carried out on a one-dimensional roughened surface and consequently Figures 11 and 12 were obtained. The usage of Al₂O₃ nano-fluid led to a CHF and HTC of 1615 kW/m² and 73 kW/m²K respectively in pool boiling test. Similarly, the usage of CuO nano-fluid led to a CHF and HTC of 1771 kW/m² and 80kW/m²K, respectively. An increase in the CHF and HTC characteristics relative to the test of the DI water can be attributed to the presence of metal oxide nanoparticles inside the base fluid. In the bubble micro layer, due to continuous evaporation of the working fluid, the fluid volume is reduced. Under those circumstances, the
concentration and collision of the nanoparticles increase, which causes the formation of a thin porous layer of particles on the surface. Also, the metallic nanoparticles within the base fluid, especially in the micro layer of the bubble, are inflamed by absorbing heat from the boiling surface. Then, they convert the absorbed energy to the kinetic one by performing random movements among the base fluid as well as collision with other particles. When the inflamed particles colliding with large bubbles formed on the boiling surface, the bubbles rupture faster and the bubble production frequency increases from a nucleation sites. The presence of submerged and dispersed nanoparticles within the base fluid extend the effective surface of heat transfer fluid. The nanoparticles which is constituted shrub-like configuration in the base fluid, transferring the heat from the boiling surface to a free surface. The use of copper oxide nanoparticles in comparison with alumina had a greater effect on the increase of HTC and CHF on one-dimensional roughened surface due to the higher nucleation sites production as well as smaller particle size.

To put it another way, Better ability to Brownian and random motions of CuO nanoparticles led to an increase in CHF and HTC in a lower temperature difference than two other surfaces, rough surface in the presence of copper oxide nanofluid, the heat flux graph is transferred to the left and shows a higher heat transfer coefficient in a constant heat flux (Figure 11). In the high heat flux which is near the critical region, where large bubbles covering the surface, the results are almost the same for both nano-fluids. Figure 6- case B and C, shows the static contact angle of the nano-fluids droplets on the roughened surface (50°<θ<60°). Although the wettability and surface hydrophilicity are considered as a beneficial factor, which causes the bubble micro-layer to dry more slowly, but in the presence of nanoparticles, the wettability and hydrophilicity of the surface become unfavorable factors. As a matter of fact, the higher the level of hydrophilicity, the higher the nanoparticles accumulate in the sites, causing blockage and reducing the density of active nucleation sites.

3.4. The roughened deposited surface in the presence of DI water

In order to create a strength porous layer with a proper thickness on boiling surface, the nano-fluids was boiled for approximately 5 hours from low to high heat fluxes gradually. As a result, the upgraded surface was made for thermal indicators such as CHF and HTC, which did not go down over time. The structure of both produced nano-coatings surface was evaluated by the SEM images in the Figure 5-case B and C. The results reveal that the surface deposited by copper oxide nanoparticles has grown more in the number of nucleation sites because the diameter of the copper oxide nanoparticles is lower than that of alumina. Deposition of a thin, sponge-shaped layer on the surface produces a super-hydrophilic surface which is visible in Figure 6, sections D and E. The capillary force of the cavities makes the liquid droplet to completely spread on the surface (10°<θ<15°) and hence leads to the more feeding of nucleation sites. Figures 13 and 14 were extracted from pool boiling test in the presence of deposited surface and DI-water. In the pool boiling test, the following results were obtained in the presence of the surface deposited by Al2O3 and CuO nanoparticles, Al2O3: (CHF: 1480 kW/m² and HTC: 67 kW/m²°C) CuO: (CHF: 1604 kW/m² and HTC: 108 kW/m²°C) Clearly, in a constant heat flux, a surface which has more nucleation sites, deposited surface by copper oxide nanoparticles, has a higher heat transfer coefficient in the Figure 14. Moreover, as shown in Figure 13, the data of this surface related to roughened surface is moved to the left, indicating that such a surface has a lower superheat temperature and higher efficiency. Also, due to the higher bubbles production and the release of jet-like bubbles through the cavities (Figure 7), boiling characteristics have increased. The sponge-shaped nanocoating which is deposited on the surface, increases the heat transfer of the boiling surface, because both the liquid and the vapor can penetrate the cavities and cool the surface down more efficiently as can be seen in the schematic Figure 15.

The presence of parallel micro-grooves on the surface, due to Capillary force of the working fluid, forces the fluid to flow through the grooves and feed the high nucleation sites produced by the nanoparticles deposition. It also delays the drying of the micro-layer bubble. The size of the nanoparticles in comparison with the average roughness of the boiling surface is one of the most important factors affecting the number of nucleation sites and bubble production in deposited surfaces. When the nanoparticle size is smaller than the mean surface roughness, the surface deposited by copper oxide nanoparticles, the entry of these nanoparticles into the grooves creates porosity and sponge formation and the movement of fluid from inside the grooves of the surface does not stop. Consequently, a significant increase in nucleation sites is observed. However, the use of alumina nanoparticles due to the larger diameter of the particles leads to less production of nucleation sites and bubble than copper oxide nanoparticles because of less ability to penetrate into the sites and micro-grooves and often deposition on the sites. This phenomenon is clearly evident in the SEM images (Figure 5) taken from the deposition surfaces.
Since the increase in the heat transfer characteristics of the nanofluids was temporary because of the formation of a thick layer of insulation on the boiling surface, the process of increasing the heat transfer characteristics was reversed by time elapsing. Therefore, by deposition of a sponge layer of alumina nanoparticles and copper oxide on the roughened boiling surface, this process is prevented. The results showed that by using the roughened surface which is deposited by alumina nanoparticle, the critical heat flux and heat transfer coefficient increased by 35.1% and 8%, respectively. Likewise, by using the roughened surface which is deposited by copper oxide nanoparticle, the critical heat flux and heat transfer coefficient increased by 46.5% and 74.2%, respectively (Figures 16 and 17). Finally, as shown in Figure 18, the use of copper oxide nanoparticles results in the best performance of the pool boiling heat transfer characteristics due to the smaller average diameter.

3.5. Bubble dynamics in different heat fluxes

The shape of generated bubbles on a roughened surface which is deposited by alumina and copper oxide nanoparticles is shown in three different heat fluxes regions in the Figure 7. In low heat fluxes, the faster and the highest activity of nucleation of sites are important. When the surface has a higher porosity due to deposition of nanoparticles especially copper oxide, nucleation sites are more active at lower temperature difference (Figures 7, 13). In medium heat fluxes, the frequency of bubbles production released from the ordinary surface was low, so the bubbles had more opportunity colliding with each other and creating a larger mushroom-shaped bubbles on the surface. But in the same heat flux, the frequency of production and separation rate of bubbles released from the surfaces deposited by nanoparticles, especially copper oxide, was higher due to the smaller diameter of the nano-particles and exit bubbles jet like from the sites and the mushroom bubble has not been shaped. In high heat fluxes (>500 kW/m²), due to the activation of both large and small nucleation sites, small bubbles are merged into each other and produce a large bubble, called dominant bubble. The dominant bubble grows bigger by swallowing other tiny bubbles on the boiling surface. By increasing the Buoyancy force, the bubble is lifted from the boiling surface and climbed upwards, then another dominant bubble will be created and replaced by the previous bubble immediately. The diameter of large bubble formed on the boiling surface depends on the density of nucleation sites. Therefore, the diameter of the dominant bubble formed on the surface deposited by copper oxide nanoparticles was larger due to the higher number of nucleation sites (Figure 19). The ascent of the dominant bubble causes the heat to be removed from the surface through the quench mechanism, so that a volume of cool fluid above the dominant bubble is replaced and pulled downward. The vortices generated by the upward movement of the bubble cause the cool fluid to flow more quickly into the sites and consequently increase the bubbles production rate.

4. Conclusion

In this study, the main goal was to develop an engineered surface suitable for long-term work. Initially, by roughness copper surface with a 600 grits sandpaper in one direction. Increasing roughness and trapping the working fluid rather than the polished surface and creating capillary grooves below the bubbles to feed more nucleation sites, as a result the values of CHF: 1095 kW/m² and HTC: 62 kW/m²°K were obtained which shows an increase in its boiling properties relative to the polished surface. A one-dimensional rough surface is used as the base level for other tests.

Alumina (30nm) and copper oxide (10nm) nanoparticles are used to produce 0.1% vol. nano fluid, due to the limitation of the base fluid heat transfer coefficient and the low number of porosity and nucleation sites on the boiling surface. The results demonstrated that the use of alumina nanoparticles on the roughened surface resulted in a 47.5% increase in critical heat flux and an increase of 17.7% in the heat transfer coefficient. Similarly, utilization of copper oxide nanoparticles on the roughened surface resulted in a 61.7% increase in critical heat flux and an increase of 29% in the heat transfer coefficient. The use of copper oxide nanoparticles showed better performance than alumina nanoparticles, because of the Brownian motion of the inflamed nanoparticles results in a significant increase in the frequency of bubble production, due to the collision of the nanoparticles with bubbles and tearing them, and this phenomenon intensified by reducing the particles diameter. Increase the heat transfer surface and heat transfer coefficient of the base fluids. Deposition of nanoparticles on the boiling surface and increase the nucleation sites.

When the nanoparticle size is lower than the average surface roughness, a further increase in the boiling heat transfer characteristics is observed.

The combination of micro-grooves and porosity, creates a mechanism that increased the nutrition of nucleation sites and a significant increase in bubble production, respectively that is suitable for long term work.
The change in the bubble dynamics was observed in the low heat flux faster formation of bubbles and increasing the number of bubbles production in moderate heat fluxes and in the high heat flux of not integrating bubbles into each other, as well as the postponement of critical heat flux.

Nomenclature

- \( d \) distance between the thermocouple center 1 and the boiling surface [m]
- \( D_b \) Bubble diameter [m]
- \( h \) Boiling heat transfer coefficient [W/m² K]
- \( K \) Thermal conductivity [W/m K]
- \( P \) Pressure [Pa]
- \( q'' \) Heat flux [W/m²]
- \( Ra \) Average roughness [μm]
- \( T \) Temperature [K]
- \( T_s \) Surface temperature [K]
- \( T_{sat} \) Fluid saturation temperature [K]
- \( U \) Uncertainty
- \( Z \) The position of the thermocouples in the heater cartridge
- \( \Delta T \) Wall superheat \((= T_s - T_{sat})\) [K]
- \( \theta \) Contact angle [°]
- \( \mu \) Viscosity [N s/m²]
- \( \rho \) Density [kg/m³]
- \( \sigma \) Surface tension [N/m]

Subscripts

- \( cr \) Critical
- \( l \) Liquid
- \( s \) Surface
- \( sat \) Saturation
- \( v \) Vapor

References


Figure 1. The schematic image of the pool boiling apparatus

Figure 2. The image of the pool boiling apparatus and position of the sensors in the heater cartridge

Figure 3. Heat flux according to surface temperature difference

Figure 4. Heat transfer coefficient according to heat flux

Figure 5. SEM images taken from rough and deposited surfaces

Figure 6. Static contact angle test for different states

Figure 7. How to form bubbles on rough surfaces and deposited surface with nanoparticles

Figure 8. Temperature variations in the heater cartridge in different heat fluxes

Figure 9. The error rate of the heat transfer characteristics with increasing heat flux

Figure 10. The image of the X-ray diffraction and the TEM taken from the nanofluids


Figure 11. Heat flux according to the surface difference temperature of nanofluids
Figure 12. Heat transfer coefficient according to the heat flux of nanofluids
Figure 13. Heat flux according to the surface difference temperature of deposited surface
Figure 14. Heat transfer coefficient according to the heat flux of deposited surface
Figure .15 A schematic of bubble formation on two rough and deposited surfaces
Figure 16. Comparison of heat flux according to the superheated temperature of all states
Figure 17. Comparison of heat transfer coefficient according to the heat flux of all states
Figure 18. Comparison of heat flux and heat transfer coefficient of all surfaces
Figure 19. The diameter of the bubble on the surfaces at high heat flux

Table Captions
Table 1. Analysis on results obtained by researchers about the effect of pool boiling of nanofluids on heat transfer characteristics

Biographies
Mehdi Mohammadi received his MSc Degrees in Mechanical Engineering from the Islamic Azad university of Science and Research Branch, Tehran, Iran (2017). He has extensive research in the field of Pool boiling of nanofluids. His major interests include energy conversion, heat and mass transfer, multiphase and Turbulence flows.

Morteza Khayat obtained his PhD in Mechanical Engineering from Sharif University of Technology (SUT), Tehran, Iran. His major interest areas are multiphase flow, heat transfer in porous media, and non-Newtonian fluid flow.
Figure 2.

Figure 3.

Figure 4.
### Figure 5.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Contact Angle</th>
<th>Image</th>
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<td>$\theta = 75^\circ$</td>
<td><img src="image1.png" alt="Image" /></td>
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<tr>
<td>B: Clean surface with CuO droplet</td>
<td>$\theta = 60^\circ$</td>
<td><img src="image2.png" alt="Image" /></td>
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<td>C: Clean surface with $Al_2O_3$ droplet</td>
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### Figure 6.
Figure 7.

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<td>B: Deposition Of Alumina nanoparticles</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
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<tr>
<td>C: Deposition Of Copper Oxide nanoparticles</td>
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<td><img src="image8.png" alt="Image" /></td>
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</table>

Figure 8.

![Graph](image10.png)

- $q'' = 89100 \text{ W/m}^2$
- $y = -0.8665x + 253.47$
- $R^2 = 0.9787$
- $q'' = 90000$
- $y = -0.8654x + 253.47$
- $R^2 = 0.9787$
- $q'' = 40000$
- $y = -0.8654x + 185.37$
- $R^2 = 0.9506$
- $q'' = 698000$
- $y = -0.8654x + 139.84$
- $R^2 = 0.9281$
- $q'' = 698000$
- $y = -0.8654x + 107.04$
- $R^2 = 0.9998$
Figure 9.

Figure 10.
Figure 14. 

Figure 15. 

Figure 16. 

15
Figure 17.

Figure 18.

Figure 19.
<table>
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<th>Nano fluids</th>
<th>Concentration</th>
<th>Particles Size (nm)</th>
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<td>0.005-0.15 Vol%</td>
<td>20-25</td>
<td>profiometer</td>
<td>Enhance in low and Deteriorated in high concentration</td>
<td>---</td>
</tr>
<tr>
<td>2009 [16]</td>
<td>TiO$_2$/ R141b</td>
<td>0.01-0.03-0.05 Vol%</td>
<td>21</td>
<td>profiometer</td>
<td>Deteriorated</td>
<td>---</td>
</tr>
<tr>
<td>2010 [17]</td>
<td>Cu/water without SDS Cu/water with SDS</td>
<td>0.25-0.5-1 Wt.%</td>
<td>10</td>
<td>SEM AFM</td>
<td>Deteriorated 48% Enhancement 75% Deterioration</td>
<td></td>
</tr>
<tr>
<td>2011 [18]</td>
<td>$\gamma$-Fe$_2$O$_3$/Water</td>
<td>0.1 Wt.%</td>
<td>10</td>
<td>SEM AFM</td>
<td>Deteriorate or Enhance related to thickness of deposition 90% Enhance</td>
<td></td>
</tr>
<tr>
<td>2012 [19]</td>
<td>ZnO/EG</td>
<td>0.5-3.75 Vol%</td>
<td>30-50</td>
<td>SEM</td>
<td>22% Enhance Enhance with increase concentration</td>
<td></td>
</tr>
<tr>
<td>2015 [20]</td>
<td>rGO/Water</td>
<td>0.01-0.3 gr/l</td>
<td>322</td>
<td>XRD SEM FI-IR</td>
<td>--- 145-245% Enhance</td>
<td></td>
</tr>
<tr>
<td>2016 [21]</td>
<td>CNT/Water</td>
<td>0.1-0.3 Wt.%</td>
<td>$\varnothing(10-20\text{nm}) \times L(1.5-2\mu m)$</td>
<td>TEM XRD SEM</td>
<td>Deteriorated Enhancement</td>
<td></td>
</tr>
</tbody>
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