Influence of nanoparticles deposition on surface roughness and heat transfer characteristics of nanofluids – A review

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ABSTRACTS

The inherent low thermal conductivity of working fluids used in transferring heat from energy system makes the performance of the system less efficient. The introduction of nanoparticles into the working fluid enhances the thermal conductivity of the fluid, thereby improving the overall performance of the energy system. Deposition of nanoparticles on the heat transfer surface of the heat exchanger occurs and this affects the mechanism of bubble formation, wettability, surface roughness of the heating surface and the overall heat transfer coefficient. In this review, the use of nanofluid showed improvement in the critical heat transfer flux (CHF) of the heat transfer fluid while the deposition of nanoparticles on the heater surface enhanced the wettability for pool boiling but caused deterioration in the heat transfer. The influence of nanoparticles deposition on surface characteristics and heat transfer coefficient during single and two phase flows in flow boiling needs to be further investigated.

Keywords: Nanofluids, bubble formation, wettability, heat transfer coefficient surface roughness,

1. Introduction

Enhancement of heat transfer is essential in energy systems such as nuclear reactors, refrigeration and air-conditioning, bio-engineering reactors, heat pumping systems and high power electronic components. The need to develop high performance and energy efficient thermal system, with reduced process time and high thermal rating has lead researchers to carry out various studies on potential methods of enhancing heat transfer processes in thermal systems. Several factors which govern the heat transfer performance of energy systems are [1–4]:

1. Thermophysical properties of the heat transfer fluid such as density, viscosity, thermal conductivity, surface tension and specific heat capacity
2. Properties of the material used for the heat transfer surface such as surface roughness, wettability, surface geometry and orientation
3. Working system properties such as pressure, temperature gradient between the surface and the fluid
4. Rate of bubble growth, departure and movement on the surface
5. Interaction between the fluid and the surface
Several approaches such as application of vibration to the surface, increase in flow rate, utilization of extended surfaces such as fins, use of micro channels, and altering the thermophysical properties and dynamics of the fluids are being used to enhance the heat transfer process and overall performance of industrial processes [5-7]. For heat exchangers, the extension of the surface and increase in the rate of fluid flow are mostly used in the improvement of system’s performance but these methods have led to unacceptable enlargement in the size of the energy system and increase in pumping power respectively. Modification of the thermophysical properties especially the thermal conductivity of heat transfer fluid is important in the improvement of the energy systems performance. To achieve this, several researches have been conducted and one of which is the addition of metal and its oxides into the working fluid of an energy system. [8] dispersed micro-sized particles into the heat transfer fluid which increased the thermal conductivity of the fluid considerably but it was not sustainable due to solid particles settling rapidly and depositing on the heater surface hereby creating a layer of particles on the surface. Hence, this reduced the coefficient of heat transfer of the fluid and eroded the surface rapidly. The large size of the particles also caused clogging of the narrow cooling channels and considerably caused the pressure drop in the fluid to increase [9]. These observations hindered further research on the use of micro-sized solid particles in heat transfer fluids for heat transfer enhancement.

Nanofluids were introduced by [5] to overcome the challenges faced with addition of micro-sized particles in heat transfer fluid. Nanofluid is formed by the dispersion of nanoparticles of nominal diameter 1 nm to 100 nm into the base fluid. A considerably increase in the thermal conductivity of the nanofluid when compared to that of the base fluid was observed [5]. Therefore, it was proposed that the challenges encountered with deposition of micro sized particles on the heater surface will most likely not occur in the use of nanoparticles given that the nanoparticles are stable and uniformly distributed in the base fluid. Metals and its oxides in nanosized are mostly used in the preparation of nanofluid due to its high thermal conductivity and its application has been found to enhance the convective and conductive heat transfer and the overall system’s performance [10]. According to [11], in a laminar developing region of constant heat flux, the average convective heat transfer coefficient and flow rate increased with the increase in nanoparticle concentration when aluminium oxide nanoparticles of 45 nm and 150 nm were dispersed in water. At constant wall temperature, [12] considered the dispersion of aluminum oxide (Al₃O₃) nanoparticles in water for a circular tube. Enhancement of heat transfer coefficient was found to be caused by the random movement of the nanoparticles in the base fluid and this caused a change in the structure of the flow field of the base fluid. [13] used similar Reynold number to study the convective heat transfer of Cu/water nanofluid at nanoparticles concentration of 2 vol%. The convective heat transfer improved by 60% while the change in the friction factor was negligible for low concentration of nanoparticles.

For proper analysis of the mechanism behind the enhanced heat transfer coefficient, [14] conducted an experimental analysis on the flow boiling in subcooled region using Zinc oxide dispersed in water. The heat transfer coefficient for the nanofluid increased by 126% when compared with water while an increase in the concentration of ZnO particles caused an increase in the surface roughness by 1367%. This increment was attributed to the deposition of nanoparticles on the heater’s surface. [15] found out that the deposition of nanoparticle on the surface significantly caused deterioration in the boiling process and boiling characteristics of Al₂O₃/water nanofluid in pool boiling. It was further explained that the deposition caused alteration in the surface roughness hence changing the nucleation site density and caused impediment to bubble movement and stirring, hence affecting the heat transfer characteristics and decrease in boiling performance respectively.

From the above, it can be deduced that the dispersion of nanoparticles into heat transfer fluid has the tendency to enhance the coefficient of heat transfer of the base fluid. Despite this, the pressure drop of fluid flow in a channel and heat transfer are affected by the initial surface roughness and the
deposition of nanoparticles on the surface [4,16-17]. With this, the need to properly understand the nucleate and flow boiling heat transfer characteristics of nanofluid, the relationship between the relative size of the nanoparticles and nanoparticles deposition with respect to the roughness of the heater surface becomes eminent. Hence, this review paper helps to achieve this by addressing the effect of nanoparticle deposition on surface micro-geometry, liquid–solid interaction, wettability, the heater surface roughness for pool and flow heat characteristics and the overall heat transfer mechanism.

2. Effect of nanoparticle deposition on wettability and critical heat flux

[18] studied the influence of nanoparticle concentration, boiling duration and initial surface roughness on surface wettability while varying one parameter at a time and controlling the others using nanoparticles. The study considered using aqueous Al2O3 nanofluid; Al2O3 nanoparticles were deposited on aluminum surface of varying roughness so as to investigate the enhancement of surface wettability due to topography change. With an increase in nanoparticles concentration, the treated surface roughness increased along with the wettability of the coated surface. It was observed that boiling and nanoparticle deposition treatment leads to a surface roughness higher than the uncoated ones. It was concluded that, the roughness of coated surface is dependent on the nanofluid concentration. To analyse the critical heat flux (CHF) of the nanofluid, [19] considered R-123 refrigerant on an uncoated and Al2O3 nanoparticle-coated heater. It was observed that the surface coated with nanoparticles improved the critical heat flux by 17% and caused little alteration in the heat transfer coefficient when compared with the uncoated surface. CHF enhancement was attributed to the high wettability of R-123 refrigerant, capillarity and porosity of the fluid. The deposited nanoparticles on the surface created a porous structure on it which enhanced the rewetting process caused by the increase in capillary action.

The improvement of critical heat flux through the variation of the surface energy using nanofluids along with pure fluids was investigated [20]. Nanofluid was prepared by dispersing Al2O3 nanoparticles of volume concentrations within 0.001 g/L to 10 g/L in water and ethanol. The heater surface was systematically changed with the deposition of metal on the surface and oxidization of the surface at various degrees. The boiling curves on the various surfaces for pure fluids and ethanol and water nanofluids were considered. The analysis showed that dilute suspensions of nanoparticles degraded or had negligible effect on the boiling performance but higher concentrations of 0.5 g/L caused approximately 37% increase in the CHF. Comparing the result obtained for the water and ethanol nanofluid, the ethanol exhibited more degradation in CHF because of its better wetting system while the water nanofluid which possesses poorly wetting systems on polished copper was enhanced through dispersion of nanoparticles into the water and fouling of the surface by nanoparticles.

For nucleate boiling, [21] considered the influence of nanoparticles deposition on surface wettability using zirconia, alumina and silica nanoparticles dispersed in water. The main focus was analysis the variations in surface wettability during pool boiling and its influence on CHF. From the result, there was significant enhancement in the CHF at nanoparticle concentration of 0.1%. Deposition of nanoparticles was observed on the surface during nucleate boiling. The layer of nanoparticle deposition considerably improved the surface wettability as indicated by the decrease in the static contact angle on the nanofluid surfaces when compared with the base fluid surface. A systematic analysis on surface modification during pool boiling using Al2O3/ nanofluid was carried out by [22]. The effect of surface roughness on wettability at different concentrations, heat fluxes and boiling rate using various aluminium substrates of different initial roughness was analysed. The analyses showed that an increase in wettability occurs when the boiling durations is extended and the nanoparticle concentration is increased. The increase in wettability was ascribed to nanoparticles deposition on the surface during the process and also the growth of hydroxides. The nanofluid caused topographical and chemical modification on the aluminium surface. [23] showed that the convective
coefficient of heat transfer for water and water based nanofluid droplet decreased with the decrease in surface wettability but the droplet convective heat transfer coefficient for nanofluid was higher than that of water with the enhancement increasing with wettability but the heat transfer rate did not change as the nanoparticles concentration changed.

From the reviews, it is established that surface wettability variations caused by nanoparticle deposition signifies the foremost significant step towards identification and understanding the plausible mechanism for enhancement of heat transfer in nanofluids. Surfactant are known to be added to nanofluid to ensure stability of nanoparticles in the base fluid but most researches have not been able to separate the influence of surfactant and nanoparticles concentration on the surface wettability during the heat transfer analysis. Therefore further research will need to be conducted in this area.

3. Nanoparticles deposition on surface roughness characteristics and boiling heat transfer

The tendency of nanoparticles accumulating on the heater surface after a long period of time may cause fouling on the surface thereby causing a resistance to energy transfer. This causes reduction in heat transfer between the surface and the fluid but the CHF is likely to increase due to the increase in the surface wettability as observed in Section 2. The propensity of the increment or decrement of the surface roughness by the nanofluid depends on the size of the nanoparticle in relation to the initial surface condition. Considering the deposition of nanoparticles on the surface, the surface roughness will increase if the initial surface roughness is less than the size of the nanoparticles but when the initial surface roughness is greater than nanoparticles size, it will decrease due to nanoparticles depositing on the pores of the surface [24]. The surface structure is a function of the initial surface roughness scale and the nanoparticle size which affects the pool and flow boiling heat transfer.

3.1 Nucleate Pool Boiling

The nucleate boiling and overall heat transfer are affected by the surface geometry, surface material properties such as cleanness, orientation, thickness, finish, and type of heat transfer fluid and its wettability [2]. The commencement of nucleate boiling is governed by the size of cavities on the heater surface while nucleation characteristics are affected by the size distribution and amount of cavities existing on the heater surface [25]. Nucleate boiling thermal performance is also affected by the aging and roughening or addition of cavities on the heat transfer surface [26-28]. The influence of surface roughness and surface material on nucleate pool boiling was analysed using two different refrigerants namely, R-123 and R-134a at various reduced pressures and stainless steel, brass and copper cylindrical surfaces [2]. The rough surface exhibited better boiling thermal performance when compared to the smooth surface at low heat fluxes but this trend changed for the high heat flux. The slope between the heat transfer coefficient and heat transfer was largely dependent on the surface material and it was higher in copper and brass but lower in stainless steel. Using horizontal circular plates of copper, brass and aluminum [16] experimentally studied the influence of surface material on nucleate pool boiling at different heat fluxes ranging from 8 – 200 kW/m². In the analysis it was revealed that the surface material have significant effect on nucleate pool boiling. Copper showed the highest heat transfer coefficient while the least was aluminium. At low heat fluxes, there was negligible variance in the heat transfer of the brass, copper and aluminum. At high heat fluxes, copper exhibited 23% improvement in thermal performance than aluminium and 18% better than brass.

The deposition of nanoparticles on surface can affect nucleate pool boiling. The influence of nanoparticle layering on heat transfer surface using ZnO/water nanofluid on horizontal surface was investigated [29]. The result initially exhibited 24% heat transfer enhancement when compared to water on an unroughened surface. As the experiment proceeded, nanoparticles layering occurred on the surface thereby causing a steady decline in rate of heat transfer displaying a measured drift that is contrary to that of water. The suspension of nanoparticles on the surface caused a suppression of
bubble formation and motion thereby causing a decrease in heat transfer rate. It was found that an increase in surface roughness caused by nanoparticle layering can significantly enhance boiling for the base fluid and to some extent decrease performance for the nanofluid. The analysis of the effect of various ranges of nanoparticle concentration, surface roughness and heat flux on the boiling heat transfer coefficient in pool boiling using Al\(_2\)O\(_3\) and water showed that the surface was covered with tiny porous layer of Al\(_2\)O\(_3\) deposit. This deposition modified the size of the surface cavities which affected the heat transfer coefficient of the nanofluid but the surface roughness, boiling heat transfer, nucleation site density were improved in the smooth surface because the deposited nanoparticles size was larger than the surface roughness. The variation in coefficient of heat transfer for Al\(_2\)O\(_3\) nanofluid and water decreased with heat flux. At lower heat flux, the creation of nucleation was active in the larger cavities while at higher heat flux, the creation of nucleation was active at smaller cavities [30]. [15] investigated the effect of water/Al\(_2\)O\(_3\) nanofluids with nanoparticle diameter of 20 nm on pool boiling in a horizontal tubular heater having different surface roughness at atmospheric pressure. From the analysis, it was observed that nanoparticles deposition on the surface modified the surface wettability and distribution of active nucleation sites, thereby causing deterioration in the boiling characteristics of the fluid. [24] also confirmed that the heat transfer coefficient of Al\(_2\)O\(_3\)/water nanofluid on a horizontal highly smooth flat surface is lower than that of water. To give a further explanation to the reason behind the deterioration of the boiling heat transfer coefficient, the surface roughness of the same samples were measured for water, 5% and 4% concentration of Al\(_2\)O\(_3\) nanofluid. It was observed that the increase in nanoparticle concentration caused a decrease in the coefficient of heat transfer. This observation was attributed to the deposition of nanoparticles on the surface which caused reduction in the number of active nucleation sites with variation of surface roughness value. [31] conducted an experimental analysis on the transient nature of nanoparticle deposition and its influence on the heat transfer coefficient in pool boiling. Aluminium oxide of nanoparticle size of 40 – 50 nm was dispersed in water at concentration of 0.01, 0.1 and 0.5 vol. %. The pool boiling experiment was done on a horizontal flat copper surface. The same nanoparticle-deposited (NPD) surfaces were also considered for the pool boiling experiment for water. It was observed that the rate and uniformity of particles deposition depended on the concentration of nanoparticles dispersed in water. For low nanofluids concentration (0.01 vol. %), the deposition of particles occurred at a slower rate, thereby, increasing the heat transfer rate.

From the review, it is established that the deposition of nanoparticles on the surface affects the surface roughness and coefficient of heat transfer in nucleate boiling and the size of nanoparticles plays a significant role in the boiling process. The mechanism behind the enhancement or deterioration of coefficient of heat transfer with varying heater surface roughness still remains unclear. [32] conducted an experimental study to further understand the mechanism behind the boiling heat transfer enhancement/deterioration nanofluid over vertical tubes. Aluminium oxide nanoparticles of diameter 150 nm and 47 nm were used for the study while average surface roughness of 48 nm, 98 nm and 524 nm were considered. Due to the enhancement and deterioration in the boiling heat transfer, the surface particle interaction parameter (SPIP) was introduced. This parameter is the proportion of the average surface roughness to the average nanoparticle diameter. It was explained that the maximum deterioration in pool boiling performance occurred when the SPIP value is near unity.

[33] developed a dimensionless heat transfer coefficient for pure fluid relating to the surface roughness and heat flux shown in Equation (1)

\[
\frac{n}{n_0} = C \cdot F(P_r) \cdot \left( \frac{q}{q_0} \right)^n
\]  

Equation (1)

Where \(n_0\), \(q_0\) and \(R\_a\_0\) are the specific heat transfer coefficient the fixed reference heat flux and the reference value for roughness, respectively. Value for constant C is given in Equation (2).
\( C = \left( \frac{R_a}{R_{a0}} \right)^{0.1333} \) \hspace{1cm} (2)

\( R_{a0} = 0.4 \mu m \) \hspace{1cm} (3)

[34] modified the Gorenflo correction considering nanoparticle size, pressure and heat flux for pool boiling nanofluid. The heat transfer enhancement was calculated directly using the simplified Equation (4).

\[
\tilde{R} = \frac{h_{nf}}{h_{bf}} = \left( \frac{1.73 \times \frac{R_a}{dp^{0.122}}}{Ra_b} \right) = \left( \frac{1.73}{dp^{0.122}} \right)^{0.57}
\] \hspace{1cm} (4)

The result showed that the heat removal from the surface in the pool phenomena is enhanced. The nanoparticles cluster formation and agglomeration increased the surface roughness thereby improving the rate of heat removal.

3.2 Flow boiling
Convective and nucleate boiling are the major element in flow boiling heat transfer. The effect of surface roughness on the pressure drop and flow boiling heat transfer was investigated in a three microchannel heat sinks [35]. At a lower heat flux, the surface roughness minor impact on the saturation boiling heat transfer and the boiling. [36] also considered the effect of surface roughness on flow boiling heat transfer, pressure drop and instability in microgap heat sink. From the result, it was concluded that the surface roughness in the microgap heat sink has no effect on the pressure drop. However, the inlet pressure instability and inlet pressure fluctuation increased with increase surface roughness at larger microgap heat sink but the bubble nucleation site density and heat transfer coefficient increase with surface roughness.

The effect of nano-sized particles deposition on the flow boiling heat transfer characteristics has not been fully explored in existing literatures. More investigations needs to be conducted to properly comprehend the influence of nanoparticles deposition on surface characteristics and the coefficient flow boiling heat transfer during single and two phase flows.

4. Conclusion and recommendation
The impact of nanoparticles deposition on surface roughness and heat transfer characteristics has been reviewed. It has been established that surface wettability variations caused by nanoparticle deposition signifies the foremost significant step towards identification and understanding the plausible mechanism for heat transfer enhancement in nanofluids. Further studies needs to be conducted to properly understand the nucleate and flow boiling heat transfer characteristics of nanofluid with respect to relative size of the nanoparticles and the roughness of the heater surface. For the nucleate boiling heat transfer analysis, the presence of nanoparticles in the heat transfer fluid affected the heat transfer characteristics of the fluid and surface roughness of the heat transfer surface but there was discrepancy on whether nanoparticles enhanced, deteriorated or caused the heat transfer coefficient to remain the same. Therefore, a full understanding on the mechanism behind the enhancement or deterioration of heat transfer coefficient with varying heater surface roughness and the influence of nanoparticles deposition on bubble growth and size and nucleation process still remains unclear. There are insufficient studies on the consequences of surface roughness and nanoparticle size on heat transfer coefficient during flow boiling. Hence, more research works need to be conducted to study the influence of deposition of nanoparticles on the change in surface roughness, wettability, flow boiling heat transfer characteristics and pressure drop.
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