

Pool Boiling Heat Transfer Using Nanofluids

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Revised on: 25/3/2014 & Accepted on: 8/1/2015

ABSTRACT

Nucleate pool boiling regime can be considered as one of the most effective ways to make a viable great amount of heat exchange in a relatively small area. To investigate the characteristics of HTC (Heat Transfer Coefficient) enhancement using nanofluids, pool boiling HTC experiments of two water – based nanofluids with alumina Al_2O_3 and titanium TiO_2 were performed using electrically heated flat plate and heating element made of stainless steel under atmospheric pressure. Systematic experiments were carried out with pure water and nanofluids containing, Al_2O_3 and TiO_2 nanoparticles in different concentrations of (0.05w %, 0.1w %, 0.3 w%, and 0.5 w %). A comparison is made between nucleate boiling of pure water and a widely used correlation proposed in 1952 by Rohsenow is done. The results show good correspondence. Pool boiling heat transfer coefficient and phenomena of nanofluids are compared with those of pure water. The experimental results show increase in the heat transfer coefficient value and decrease in the surface superheat temperatures of heating element. This value increases with increasing nanoparticles concentration. The best nucleate boiling heat transfer performance enhancement is generally observed to be at Al_2O_3 nanofluid, compared to that of TiO_2 nanofluid and pure water.

Keywords: Heat transfer _ Nucleate pool boiling _ Al_2O_3 and TiO_2 _ Nanofluid

انتقال الحرارة بالغليان الحوضي باستخدام موانع النانو

الخلاصة:

النظام المغلي النووي يمكن ان يعتبر واحد من اكثر الطرق فعالية لجعل كمية كبيرة من تبادل الحرارة في مساحه صغيرة نسبيا . لتحري تحسين خصائص معامل انتقال الحرارة تستعمل الموانع النانوية في تجارب قياس معامل انتقال الحرارة بغليان البركة. اثنان من الموانع النانوية ذو الاساس المائي هما أكاسيد الالومينا والتيتانيوم ويتم ذلك باستعمال مسخن كهربائي على شكل صفيحة مستوية مصنوعة من الفولاذ المقاوم تحت الضغط الجوي .

نفذت التجارب مع الموانع النانوية ذو الاساس المائي باستخدام نوعين من الجسيمات الصغيرة جدا (Nano particles) بتركيز مختلفة (0.05, 0.1, 0.3, 0.5 %) وبنسب وزنية من TiO_2, Al_2O_3 . تمت مقارنة الغليان

التنوي للماء النقي مع المعادلة التجريبية المقترحة في 1952 من قبل العالم Rphsenow وكانت النتائج متوافقة مع الماء النقي .
تمت مقارنة معامل انتقال الحرارة بغليان البركة في ظاهرة الموائع النانوية مع الماء النقي حيث اظهرت النتائج زيادة بقيم معامل انتقال الحرارة والنقصان في درجة حرارة السطح لعنصر التسخين تلك القيم تزداد مع زيادة تركيز الجسيمات الصغيرة نسبياً (النانوية).
معدل انتقال الحرارة في منطقة الغليان المتنوي يعتمد بقوة على عدد مواقع التنوي الفعالة على السطح ومعدل تكوين الفقاعات على كل موقع.
الافضل في تحسين اداء انتقال الحرارة في الغليان التنوي بصورة عامة لوحظ عند استخدام المائع النانوي Al_2O_3 100% اعلى المائع النانوي TiO_2 - 81,82 % والماء النقي.

INTRODUCTION

Boiling heat transfer is defined as a mode of heat transfer that occurs with a change in phase from liquid to vapor. Pool boiling is boiling on a heating surface submerged in a pool of initially quiescent liquid. While flow boiling is a boiling in a flowing stream of fluid.[1]

Boiling heat transfer is used in a variety of industrial processes and applications, such as refrigeration, power generation, heat exchangers, cooling of high-power electronics components and cooling of nuclear reactors. Enhancements in boiling heat transfer processes are vital, and could make these typical industrial applications, previously listed, more energy efficient. The intensification of heat-transfer processes and the reduction of energy losses are hence important tasks, particularly with regard to the prevailing energy crisis. [2]

Nanofluid

Nanofluids are a new class of nanotechnology-based heat-transfer fluids, engineered by dispersing and stably suspending nanoparticles (with dimensions on the order of 1-100 nm) in traditional heat-transfer fluids.

Nanofluids are prepared by suspending nanosized particles in conventional fluids and have higher thermal conductivity than the base fluids.[3]

Nanofluids have the following characteristics compared to the normal solid liquid suspensions:-

1. Higher heat transfer rate between the particles and fluids due to the high surface area of the particles
2. Better dispersion stability with predominant Brownian motion reduces particle clogging
3. Reduced pumping power as compared to base fluid to obtain equivalent heat transfer.[4]

These particles can be metallic (Cu, Au) or metal oxides (Al_2O_3 , SiO_2 , ZrO_2) carbon (Diamond, Nanotubes), glass or another material, and the base fluid being a typical heat-transfer fluid, such as water, light oils, ethylene glycol (radiator fluid) or a refrigerant. The base fluids alone have rather low thermal conductivities. [5]Figure (1) shows photo of the various nanoparticles.

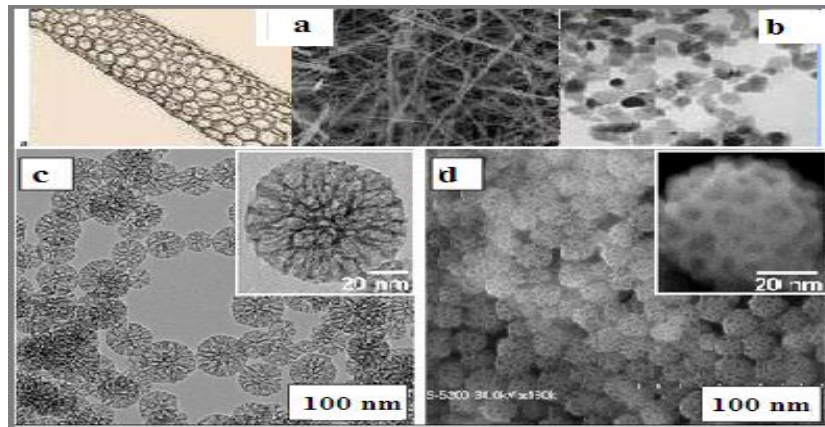


Figure.(1) Photo of various nanoparticles: (a) Carbon nanotubes, (b)TiO₂nanoparticles, (c) Silica nanoparticles in 80 nm (d) Silica nanoparticles in 45 nm. [6]

A Brief History of Nanofluids

Recent nanofluids(liquids)were first used by a group in Argonne National Laboratory USA (Choi) [7] to describe liquid suspensions containing nanoparticles with thermal conductivities, on orders of magnitudes higher than the base liquids, and with sizes significantly smaller than 100 nm.

Li et al. [8] studied boiling of water-CuOnanofluids of different concentrations (0.05% and 0.2% by weight) on copper plate. They observed deterioration of heat transfer as compared to the base fluid and attributed this fact to the sedimentation of nanoparticles which leads to the changing of radius of cavity, contact angle, and superheat layer thickness.

You et al. [9]used nanoparticles materials with concentrations from (0.001 to (0.05 g/l),they studied nucleate boiling heat transfer coefficients for water-Al₂O₃ nanofluid while boiling on plate appeared to be the same as for base fluid at (0.001 g/l) but the change is very small at (0.05 g/l).

D. Wen and Y. Ding [10],have done an experimental investigation into the pool boiling heat transferof aqueous based alumina nanofluids. Systematic experiments were carried out to formulate stable aqueous based nanofluids containing γ -alumina nanoparticles (primary particle size 10–50 nm), and to investigate their heat transfer behaviour under nucleate pool boiling conditions. The results show that alumina nanofluids can significantly enhance boiling heat transfer. The enhancement increases with increasing particle concentration and reaches ~40% at a particle loading of 1.25% by weight.

Shi et al. [11] carried out experiments with boiling of water-Al₂O₃ nanofluid and Fe-water nanofluid on horizontal, copper plate with 60 mm in diameter. The concentration of nanoparticles was 0.1%, 1%, and 2% by volume. Generally, the augmentation and deterioration of heat transfer were observed forwater-Al₂O₃ and water-Fe nanofluids, respectively.

Tu et al. [12] studied pool boiling heat transfer and CHF ofAl₂O₃-water at nanoparticle concentration (0.1%, 0.5%), and obtained a significant increase in both boilingheat transfer coefficient and critical heat flux with nanofluids.

Experimental Work

Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Figure (4) and a photo of the experimental apparatus test section is shown in fig. (5). The experiments were carried out in saturated pool boiling of water under atmospheric pressure. There was a copper coil on top of the vessel to condense the vapor. A venting hole was drilled in the middle of the vessel lid to allow atmospheric operations. A glass window was designed on one side of the vessel for visual observations. The heating surface was submerged in fluid which was made of stainless steel grad 316. The major parts of experimental apparatus were:-

- 1- Boiling vessel.
- 2- Heating Element.
- 3- Condenser.
- 4- A voltmeter and ammeter for measuring voltages and currents.
- 5- Digital temperature reader.

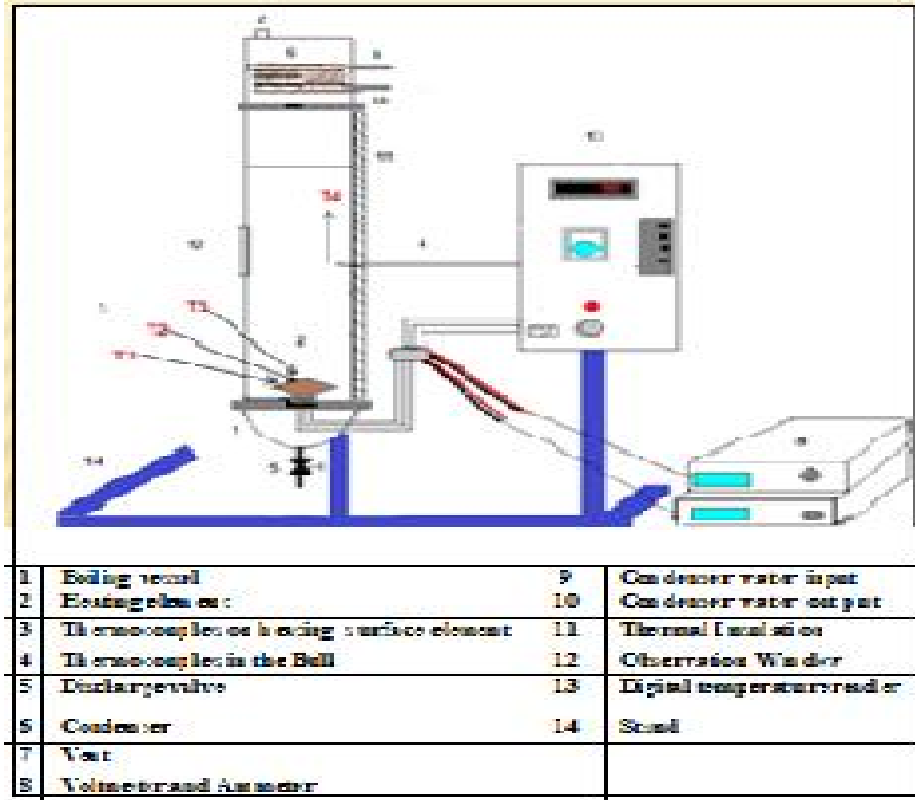


Figure. (2) Schematic diagram of the experimental apparatus

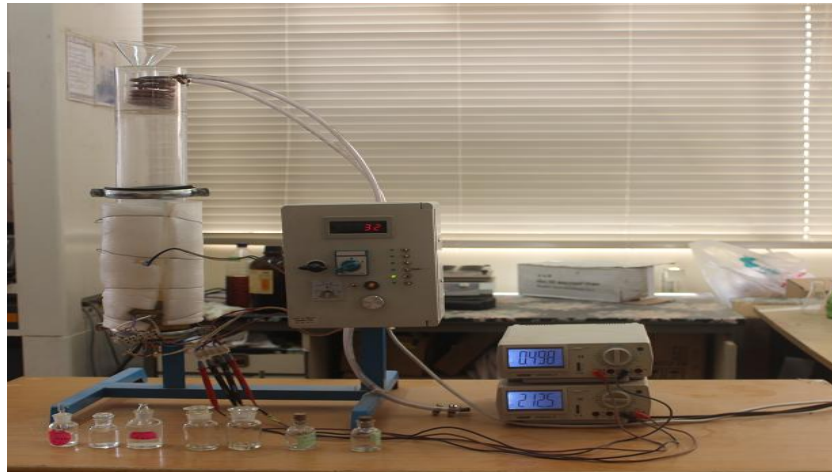


Figure. (3)General view of the experimental apparatus

To prepare the nanofluid, it is necessary to disperse the dry nanoparticles uniformly into the whole base fluid. Nanoparticle preparation procedure was as follows

Al_2O_3 and TiO_2 are used as nanoparticles, Alumina nanoparticles (Al_2O_3 alpha/gamma), of spherical form with diameter 50 nm and Titanium Oxide Nanopowder/ Nanoparticles TiO_2 (anatase/ rutile), with diameter 20 nm. While distilled water was used as a base fluid. To prepare nanofluids, nanoparticles were dispersed in pure water. Different concentrations were used in the experiment. The amounts of nanoparticles required and base fluid are mixed together by magnetic stirrer for 4 hours and in ultrasonic path for 1 hour to ensure that there are no significant, agglomerated particles inside the boiling vessel.

Experimental procedure

- 1- Measuring the heat transfer rates with out nonmaterial's
- 2- Measuring the heat transfer rate of nanofluids with different concentration. Cases of more than one heat flux were used to observe its effect on the obtained values of heat transfer coefficient.

Characterization analysis of nanoparticles

Figures (6 and 7) show the nanoparticles of Al_2O_3 and TiO_2 in the powder state, By SEM (scanningelectronmicroscopy).The nanoparticles form loose agglomerates of micrometer size. As it is well-known, nanoparticles have a strong tendency to agglomerate due to relatively strong van der Waals attraction between particles in dry and wet environments, and the result of particles agglomerate forms particle in micrometer size.

- Preparation the nanofluidas weight concentrations at (0.05, 0.1, 0.3, and 0.5) of Al_2O_3 and TiO_2 nanoparticles and the base fluid (distilled water). Figures (8 and 9) display photographs of the tested water- Al_2O_3 and water- TiO_2 nanofluids.
- The nanoparticles and distilled water were mixed in a flask using a magnetic stirrer for 2 hours and for 1 hour in an ultrasonic bath to suspend nanoparticles in base fluid. Figures (10 and 11) show images of water- Al_2O_3 and water- TiO_2 nanofluids in (wet state), by AFM (Atomic Force Microscope). After

suspending nanoparticles in distilled water in magnetic stirrer for 3 hours and for 1 hour in an ultrasonic bath, these images show the nanoparticle diameters are increased due to agglomeration between the nanoparticles in distilled water.

- To get stabilization and better dispersion of nanoparticles in base fluid, mixing time in magnetic stirrer is increased for 4 hours and then it is immersed in an ultrasonic bath for 1 hour, to disperse the nanoparticles in the base fluid and break down the agglomerates formed.
- SEM (Scanning Electron Microscope) was used after nanoparticles were dispersed in distilled water, to be sure it is well dispersed before nanofluids used in boiling experiment. Figures (12 and 13) show the Al_2O_3 and TiO_2 nanoparticles are very dispersed in base fluid (distilled water). And then nanofluid will be ready for use in the experiment.

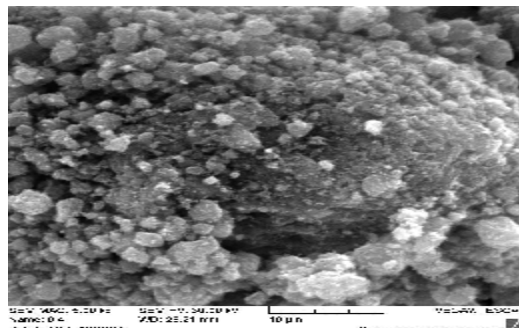


Figure (4) SEM image of Al_2O_3 powder state

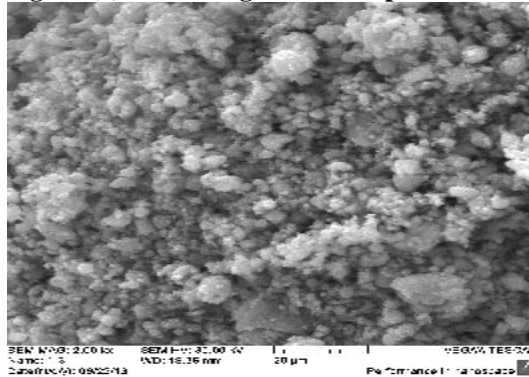


Figure (5) SEM image of TiO_2 powder state



Figure (6) Photographs of the water- Al_2O_3 nanofluids preparation



Figure (7) Photographs of the water-TiO₂ nanofluid preparation

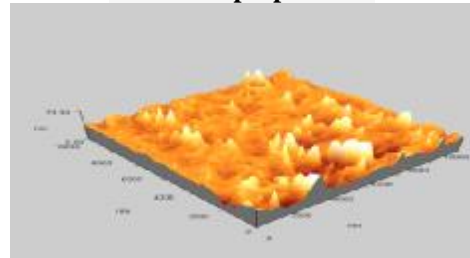


Figure (8) AFM of 0.5% Al₂O₃ nanoparticle in water (nanofluid)

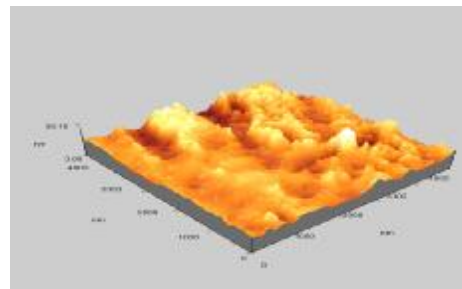


Figure (9) AFM of 0.5% TiO₂ nanoparticle in water (nanofluid)

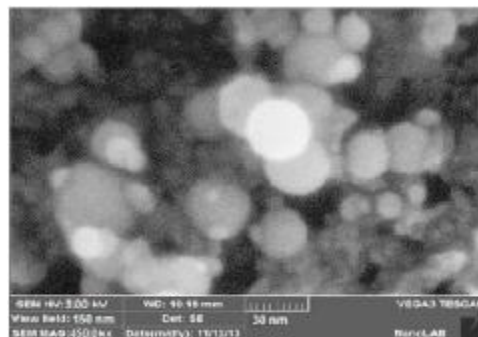


Figure. (10) SEM image of Al₂O₃ nanoparticle dispersion in water

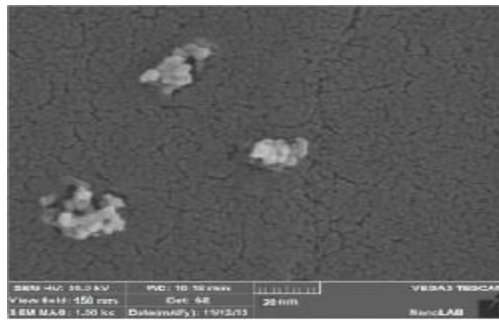
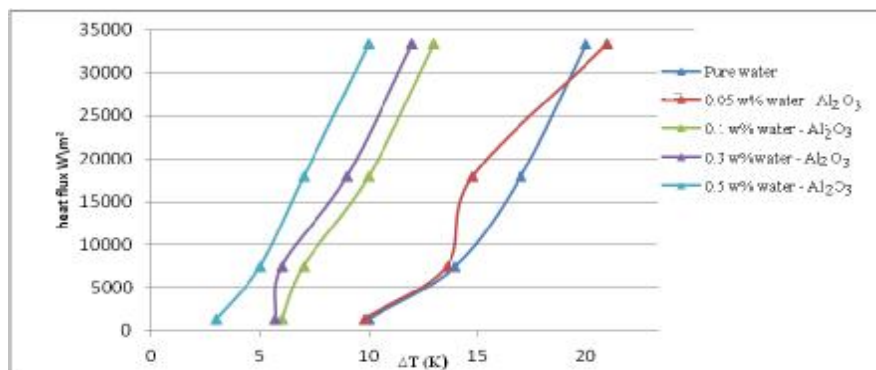


Figure. (11) SEM image of TiO₂nanoparticle dispersion in water

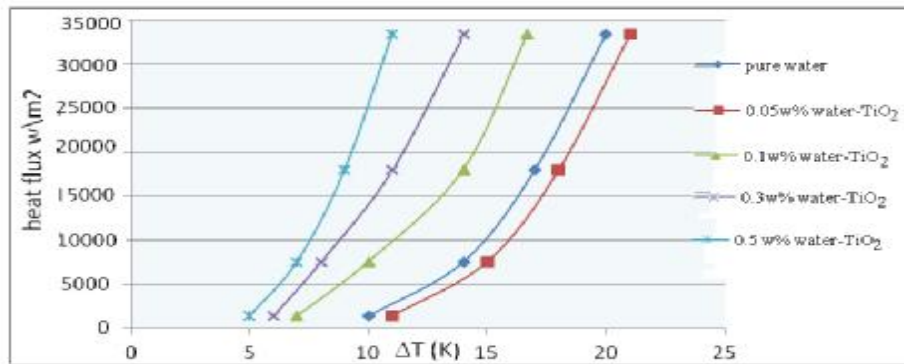
Results and Discussions

Effect of Adding Nanoparticles to Distilled Water:

The experimental data for pool boiling of various concentrations of Al₂O₃ and TiO₂ nanoparticles show that the addition of nanoparticles to distilled water shifts the nucleate boiling curve to the left indicating enhancement of heat transfer coefficient. This behavior can be seen in figures (14 and 15) compared with pool boiling of pure water. The nanoparticles addition reduces significantly the tendency of coalescence between vapor bubbles, and the large surface area is related to small nanoparticles size. Bubbles grow heavily and activate nucleation site density in nucleate pool boiling, and grow continuously and depart from heating surface. The bubbles are smaller in size but much larger in number than in the case of pure water. A decrease in the bubble size at boiling in nanofluid may be attributed to a decrease in the surface tension compared to the pure water.



Figure(12) Boiling curves at different concentrations of water –Al₂O₃ Nanofluid during pool boiling



Figure(13)Boiling curves at different concentrations of water –TiO₂ Nanofluid during pool boiling

Effect of Nanoparticle Concentrations on the Nucleate Pool Boiling Heat Transfer Coefficient (HTC)

These experiments were carried out at concentration values (0.05w %, 0.1w%, 0.3w% and 0.5w % and) of Al₂O₃and TiO₂ nanoparticles. Figures (16 and 17) show the curves of nucleate boiling heat transfer coefficient for both water-Al₂O₃ and water-TiO₂(nanofluids) which increases with increasing concentrations of Al₂O₃ and TiO₂ nanoparticle, at values (0.1w%, 0.3w% and 0.5w %). These curves of nanofluids deviate to the left from distilled water curve towards lower heating surface temperatures, Singh et al. [13] found out the presence of nanoparticle in small size and spherical shape in water makes change in fluid properties which is contact with heating surface, Change in the properties of the heating surface is by increasing the density of nucleation sites. When a nanofluid boils, the surface area of pool boiling increases if nanoparticle concentration that was dispersed in distilled water increases. Because a nanoparticle has large surface area compared with small size, then the number of bubbles increases and bubbles are formed in small size. This will be an effective catalyst for nucleate boiling sites to grow, leading to increase in the bubble column numbers that rise with heat transport to the bulk fluid, due to increase in heat transfer rate.

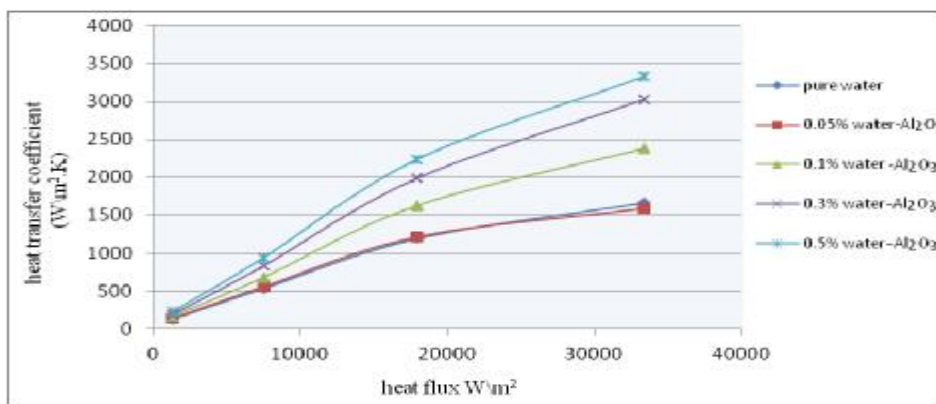


Figure (14) Comparison between experimental nucleate pool boiling heat transfers coefficient of base water and nanofluid (Al₂O₃-water) at variation weight concentrations

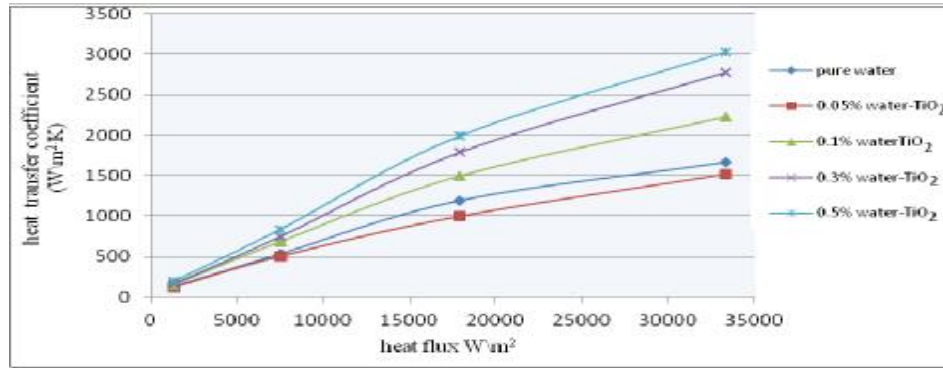


Figure (15) Comparison between experimental nucleate pool boiling heat transfer coefficient of base water and nanofluid (TiO₂-water) at variation weight concentrations

Comparison between Experimental and Predicted Data

A more traditional plot of heat flux against wall superheat is shown in Figures(18 and 19); together with the prediction by the following classical correlation, Rohsenow [14], this equation is:-

$$\frac{q}{A} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[\frac{C_{P_l}(T_s - T_{sat})}{C_{sf} h_{fg} P_{rl}^n} \right]^3$$

Comparisons between the experimental data and the Rohsenow correlation show that the correlation can potentially predict the performance with an appropriate modified fluid surface combination factor and changed physical properties of the base fluid.

These figures show the pure water results match the traditional Rohsenow correlation, and the heat transfer with nanofluids shows an enhancement in heat flux and this enhancement increases with increased nanoparticle concentrations.

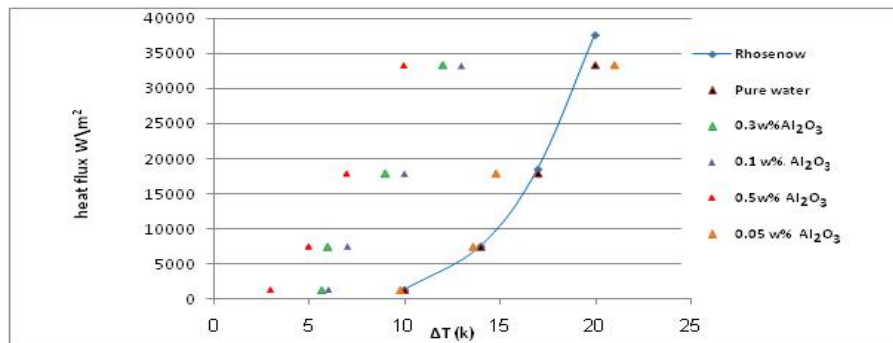


Figure (16) Comparison of experimental data with Rohsenow correlation for pure water and Al₂O₃ nanofluids at different concentrations

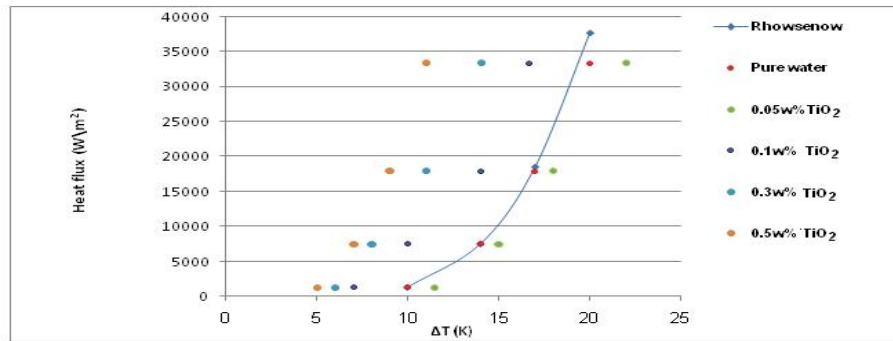


Figure (17) Comparison of experimental data with Rohsenow correlation for pure water and TiO₂ nanofluids at different concentrations

Optimum Nanofluids for Heat Transfer:

It is well known that the nanoparticles having highly thermal conductivity increase the heat transfer coefficient. The markedly different behavior of heat transfer performance for Al₂O₃ and TiO₂ nanofluid can be seen from figures (20 and 21) which give a typical enhancement plot quantifying the extent of heat transfer enhancement in nucleate boiling.

The results are graphed in the form of heat transfer coefficient defined as:

$$\frac{h_{Nf} - h_{water}}{h_{water}} = \frac{(q''_{w/\Delta T_{sat.}})_{Nf} - (q''_{w/\Delta T_{sat.}})_{water}}{(q''_{w/\Delta T_{sat.}})_{water}} = a$$

Where

a is enhancement ratio

These figures show a maximum enhancement is (66.7%) for 0.5 % weight concentration for Al₂O₃ nanofluid while the enhancement ratio is (42.8 %) for TiO₂ at the same concentration, and in both nanofluids, The enhancement ratio increases with increased nanoparticle concentrations this leads to increase in the pool boiling heat transfer coefficient.

Although Al₂O₃ and TiO₂ have the same properties, in terms of the smaller particle size, the greater the surface area, the better the particle activity and phase stability. The reasons for Al₂O₃ nanoparticle gave more enhancement than TiO₂ nanoparticle, are: ultrafine Al₂O₃ high hardness, easy dispersion and strong permeability in distilled water which results in stable form so that the dispersion is in the form of solid balls free movement while the titanium oxide nanoparticle dispersion in water is in the thin film. On the other hand, thermal conductivity of Al₂O₃ nanoparticle is higher than that of TiO₂ nanoparticle, Wei Yu and Huaqing Xie [15].

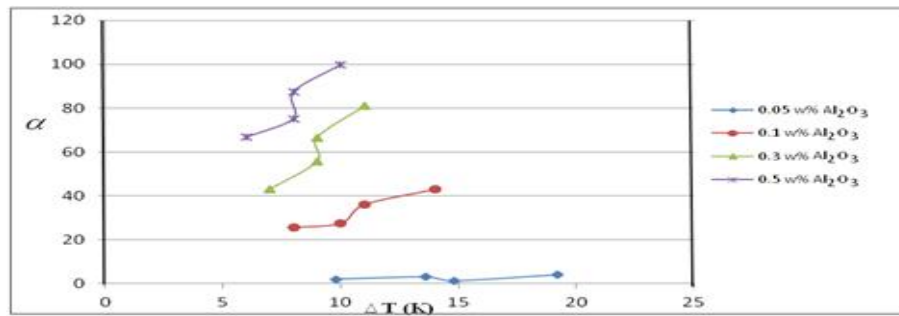


Figure. (18) Heat transfer enhancement of Al_2O_3 nanofluid with variation in heat fluxes and nanoparticle concentrations.

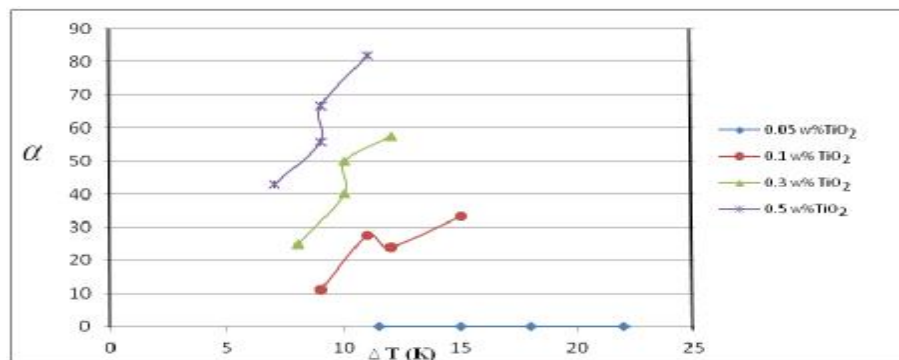


Figure. (19) Heat transfer enhancement of TiO_2 nanofluid with variation in heat fluxes and nanoparticle concentrations

CONCLUSIONS

- As expected, heat flux has a strong effect on the pool boiling heat transfer coefficient. It means that with increasing the heat flux, the pool boiling heat transfer coefficient dramatically increases. With presence of nanoparticles, higher heat transfer coefficients are reported compared to pure water.
- Heating surface temperatures decrease in nanofluid pool boiling with increasing the concentrations of nanoparticle, the pool boiling heat transfer coefficient increases.
- The heat transfer in saturated nucleate boiling of nanofluid is found to enhance considerably. The best nucleate boiling heat transfer performance enhancement is generally observed to be when using Al_2O_3 nanofluid, compared to that of TiO_2 and pure water.
- The maximum enhancement in nucleate pool boiling is found to be dependent upon wall heat flux (or temperature difference) and nanoparticles low concentration.
- Whenever there is increase in nanoparticles dispersion in pure water, there is increase in heat transfer coefficient. This enhancement is characterized by a rapid departure of smaller-sized, regularly shaped bubbles from the heated surface, and an increase in the number of bubbles.

NomenclaturesA area, m²

C concentration [v/v]

C_{sf} Surface fluid combinationd_b Bubble departure diameter, m

I current, A

K Thermal conductivity, W/m.k

q Heat amount, W

q" Heat flux W/m²

T Temperature, K

V Voltage, V

ΔT_{sa} Wall superheat or temperature difference [T_s – T_{sat}] K**Subscripts**

b bulk

e equilibrium of vapor

l liquid

Sat. Saturation

S Surface temperature

v vapor

Abbreviation

HTC Heat Transfer Coefficient

HTFs Heat Transfer Fluids

nm nanometer

Nf Nanofluid

CHF Critical Heat Flux

Greek symbols

α Enhancement of heat transfer coefficient

ν Kinematic viscosity m²/s

μ Dynamic viscosity g/m.s

ρ Density kg/m³

σ Surface tension N/m

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