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Pool Boiling Heat Transfer Using Nanofluids

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ABSTRACT

Nucleate pool boiling regime can be considered one of most effective ways to make viable a 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_2were 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_2nanofluid and pure water.

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

انتقال الحرارة بالغليان الحوضي باستخدام موائع 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 الموائع النانويةفي تجارب قياس

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معامل انتقال الحرارة بغليان البركة.اثنان من الموائع النانوية ذو الاساس المائي هما أكاسيد الالومينا والتيتانيوم ويتم ذلك باستعمال مسخن كهربائي على شكل صفيحه مستوية مصنوعة من الفولاذ المقاوم تحت الضغط الجوي .

نفذت التجارب مع الموائع النانوية ذو الاساس المائيباستخدام نوعين من الجسيمات الصغيرة جدا(Nano particles) بتراكيز 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 في1952 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 لعنصرالتسخين تلك القيم تزداد مع زيادة تركيز الجسيمات الصغيرة نسبيا(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 تحسن اداء انتقال الحرارة في الغليان التنوي بصورة عامة لوحظ عند استخدام المائع النانوي Al_2O_3 100% اعلى المائع النانوي TiO_2 بـ 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 solidliquid 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 pumpingpower 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 variousnanoparticles.

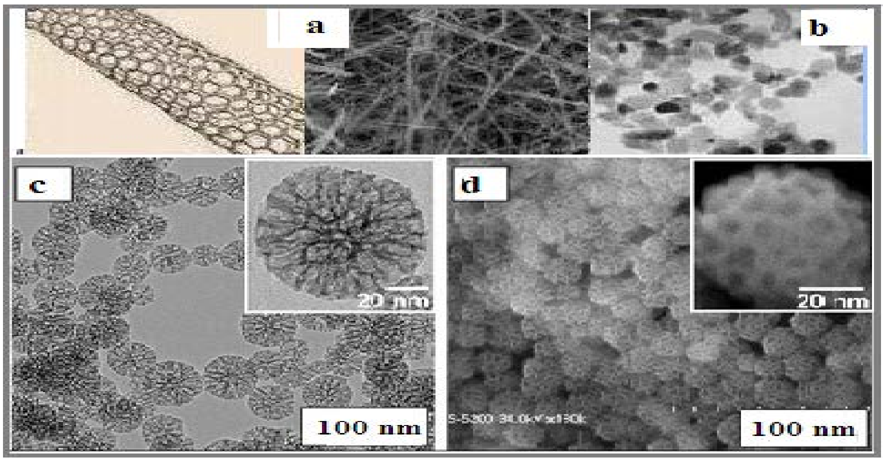


Figure.(1) Photo of various nanoparticles: (a) Carbon nanotubes, (b)TiO_2nanoparticles, (c) Silica nanoparticles in 80 nm (d) Silica nanoparticles in 45 nm. [6]

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 concentrationsfrom (0.001) to (0.05 g/l),they studied nucleate boiling heat transfer coefficients for water-Al_2O_3 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 anexperimental 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 co 4 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-Al_2O_3 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-Al_2O_3 and water-Fe nanofluids, respectively.

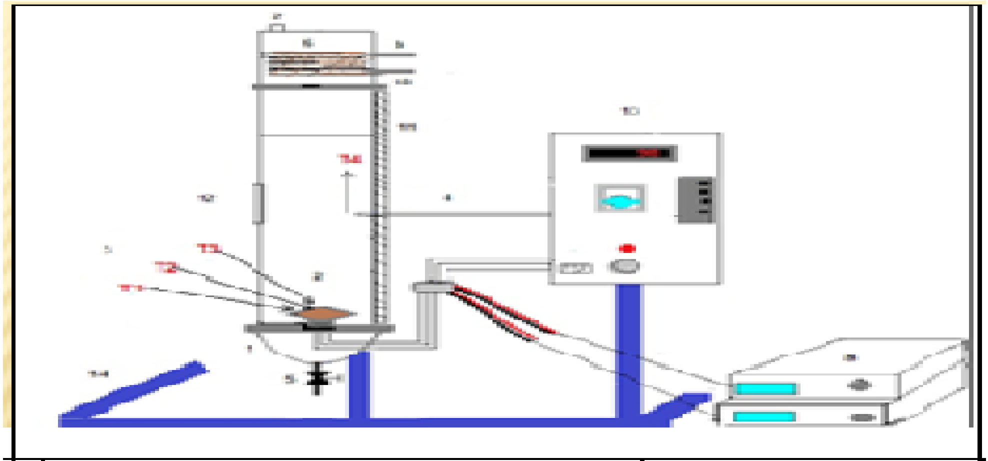
Tu et al. [12] studied pool boiling heat transfer and CHF ofAl_2O_3-water at nanoparticle concentration (0.1%, 0.5%), and obtained a significant increase in both boilingheat transfer coefficient and critical heat flux with nanofluids**.**

Experimental Work

Experimental Apparatus

A schematic diagram of the experimental apparatus is shown infigure (4)and a photoof the experimental apparatus test sectionis shown in fig. (5).The experiments were carried out in saturated pool boiling ofwater under atmospheric pressure.There was a coppercoil 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 stainlesssteel grad 316. The major parts ofexperimental apparatuswere:-

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



1	Boiling vessel	9	Condenser water input
2	Heating element	10	Condenser water output
3	Thermocouples on heating surface element	11	Thermal Insulation
4	Thermocouples in the Bulk	12	Observation Window
5	Dischargevalve	13	Digital temperaturereader
6	Condenser	14	Stand
7	Vent		
8	Voltmeterand Ammeter		

Figure. (2) Schematic diagram of the experimental apparatus

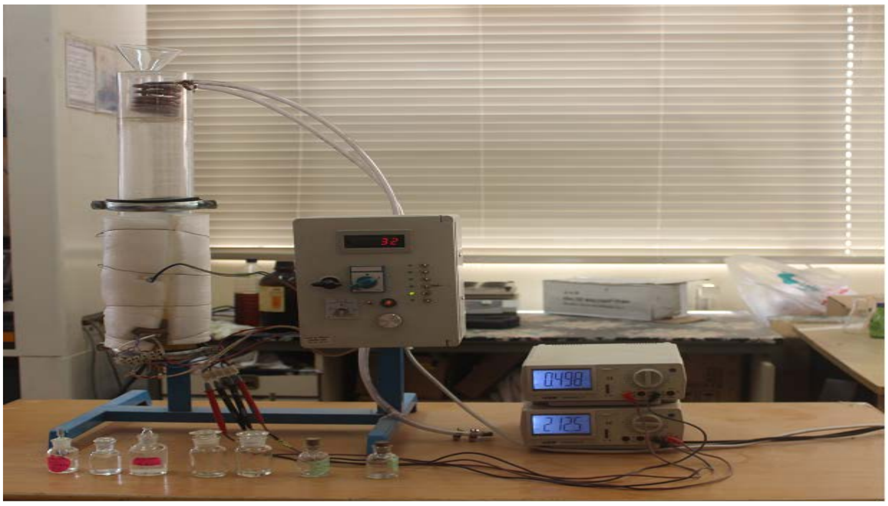


Figure. (3)General view of the experimental apparatus

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_3alpha/gamma), of spherical form with diameter 50 nm and Titanium Oxide Nanopowder/ NanoparticlesTiO_2(anatase/ rutile), with diameter 20 nm. While distilled water was used as a base fluid. To prepare nanofluids,nanoparticles were dispersedin 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 insidethe boiling vessel.

Experimental procedure

1- Measuring the heat transfer rates withoutnonmaterial'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, bySEM (scanningelectronmicroscopy).The nanoparticles form loose agglomerates of micrometer size. As 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 distillated 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 distillated water.

- To get stabilization and better dispersion of nanoparticles in base fluid,mixing time in magnetic stirrer isincreased 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 distillated 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 (distillated water). And then nanofluid will be ready for use in the experiment.

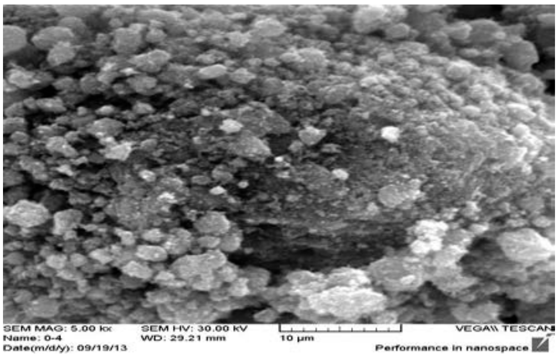


Figure (4) SEM image of Al2O3 powder state

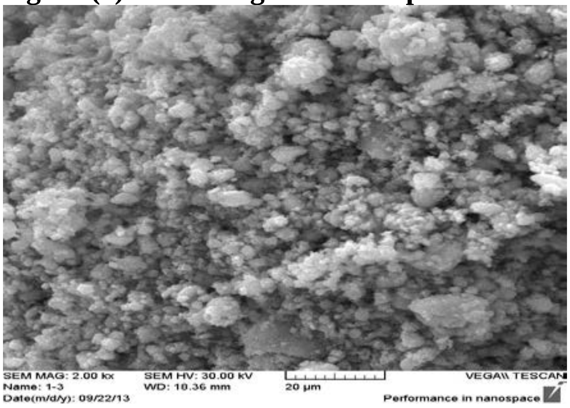


Figure (5) SEM image of TiO_2powderstate

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

Figure (7) Photographs of the water-TiO_2 nanofluidspreparation

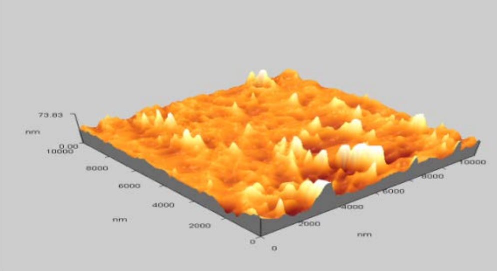


Figure (8) AFM of 0.5%Al2O3 nanoparticle in water (nanofluid)

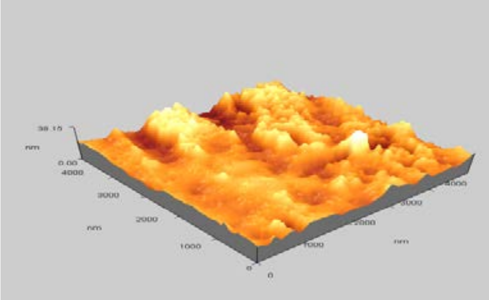


Figure (9) AFM of 0.5%TiO2 nanoparticle in water (nanofluid)

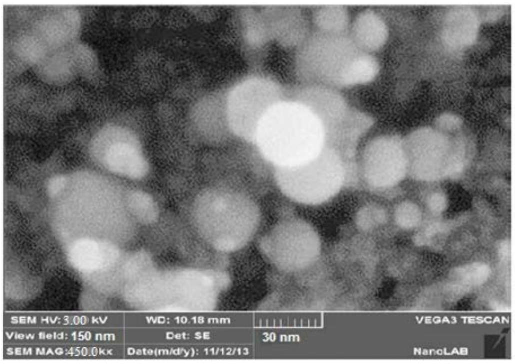


Figure. (10) SEM image of Al_2O_3 nanoparticle dispersion in water

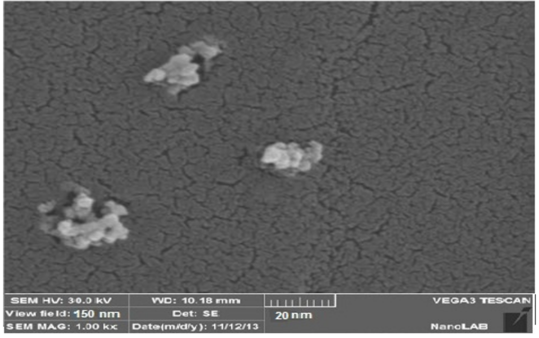


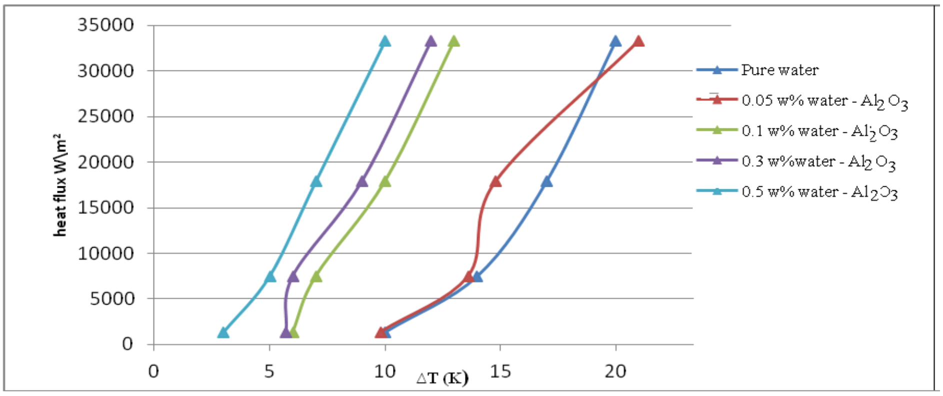
Figure. (11) SEM image of TiO_2nanoparticle dispersion in water

Results and Discussions

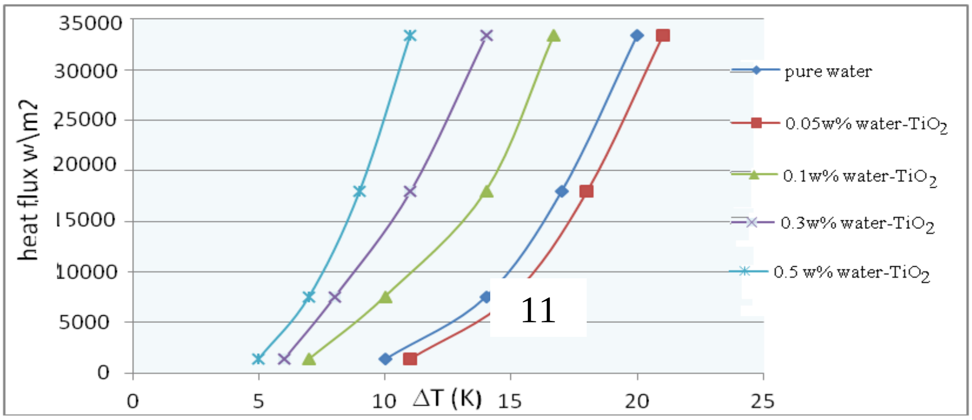
Effect of Adding Nanoparticles to Distilled Water:

The experimental data for pool boiling of various concentrations ofAl_2O_3 and TiO_2 nanoparticlesshow that the addition of nanoparticles to distilled water shifts the nucleateboiling curve to the left indicating enhancement of heat transfer coefficient.

This behavior can be seenin 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 growheavily 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 –Al_2O_3 Nanofluid during pool boiling



Figure(13)Boiling curves at different concentrations of water –TiO_2 Nanofluid during pool boiling

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

Theseexperiments were carried out at concentration values (0.05w %, 0.1w%, 0.3w% and 0.5w % and) of $Al_2O_3$and TiO_2 nanoparticles.Figures (16 and 17) show the curves of nucleate boiling heat transfer coefficient for both water-Al_2O_3 and water-TiO_2(nanofluids) which increases with increasing concentrations ofAl_2O_3 andTiO_2 nanoparticle,atvalues (0.1w%, 0.3w% and 0.5w %). These curves of nanofluids deviate to the left from distilled water curve towards lowerheating 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 bubblesincreases and bubbles are formedin 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.

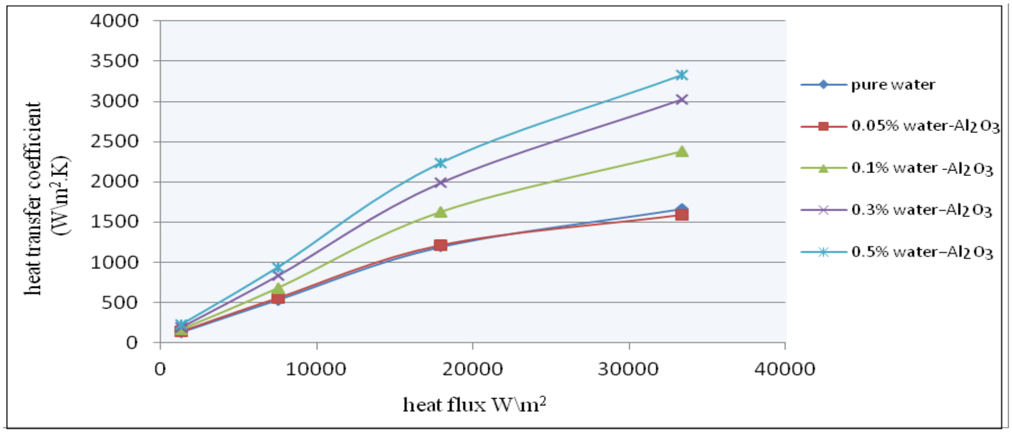


Figure (14) Comparison between experimental nucleate pool boiling heat transferscoefficient of base water and nanofluid (Al_2O_3-water) at variation weight concentrations

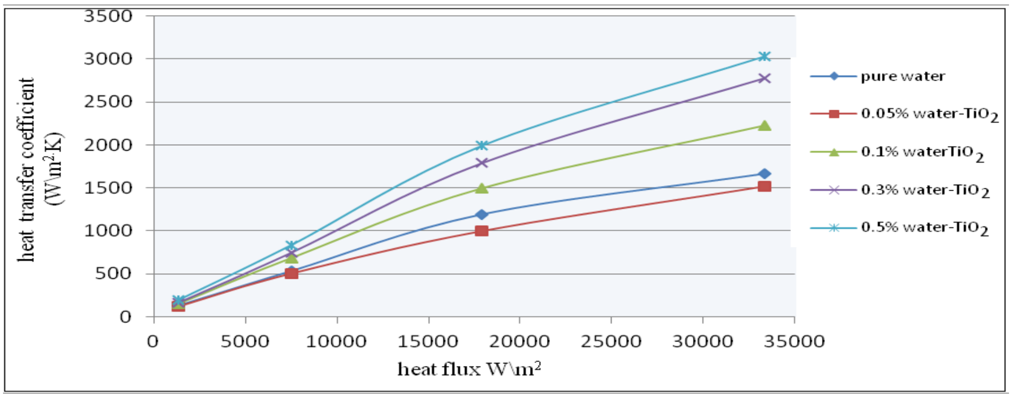


Figure (15) Comparison between experimental nucleate pool boiling heat transfer coefficient of base water and nanofluid (TiO_2-water) at variation weight concentrations

Comparsion between Expermintal and Predicted Data

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

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

Comparisons between theexperimental data and the Rhosenow correlation showthat the correlation can potential' ''ct the performancewith an appropriate modified fluid surface combinationfac 13 changed physical properties of thebase fluid.

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

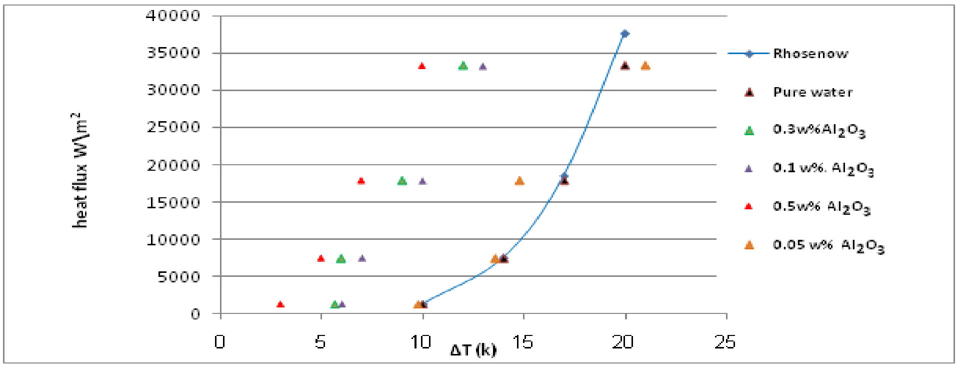


Figure (16) Comparison of experimental data with Rohsenow correlation for pure water and Al_2O_3 nanofluids at different concentrations

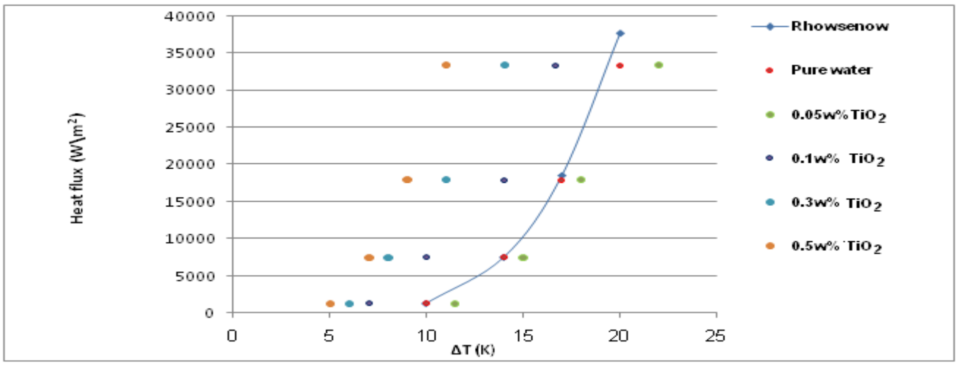


Figure (17) Comparison of experimental data with Rohsenow correlation forpure water and TiO_2nanofluids at different concentrations

Optimum Nanofluids for Heat Transfer:

Itis well known that the nanoparticles having highly thermal conductivity increase the heat transfer coefficient. The markedly different behavior of heat transfer performance for $Al_2O_3$and TiO_2nanofluid can be seen from figures (20 and 21) which give a typical enhancement plotquantifying theextent of heat transfer enhancement in nucleate boiling.

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

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

Where

α is enhancement ratio

These figures show a maximum enhancement is (66.7%) for 0.5 % weight concentration for Al_2O_3nanofluid while the enhancement ratio is (42.8 %) for TiO_2 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 Al_2O_3andTiO_2havethe same properties, in terms of thesmaller particle size, the greater the surface area, the better the particle activity and phase stability.The reasons for Al_2O_3nanoparticle gave more enhancement thanTiO_2nanoparticle, are: ultrafine Al_2O_3high hardness, easy dispersion and strong permeability in distillated water which results in stable form so that the dispersion is in the form of solid balls free movement whilethe titanium oxide nanoparticle dispersion in water is in the thin film. On the other hand, thermal conductivity of Al_2O_3 nanoparticle is higher than that of TiO_2 nanoparticle, Wei Yu and Huaqing Xie [15].

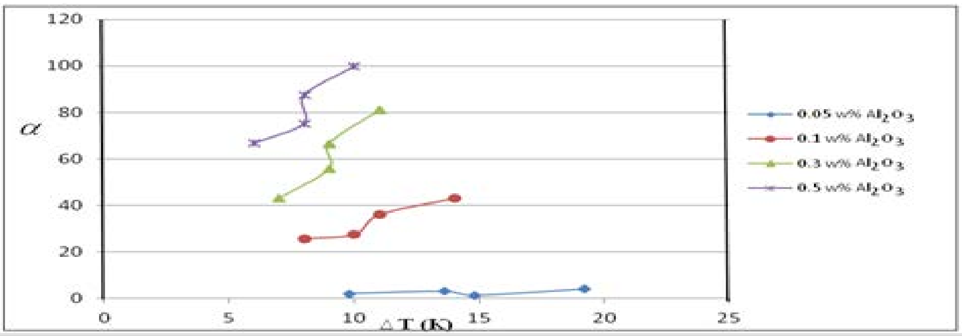


Figure. (18) Heat transfer enhancement of Al_2O_3 nanofluid withvariation in heat fluxes and nanoparticle concentrations.

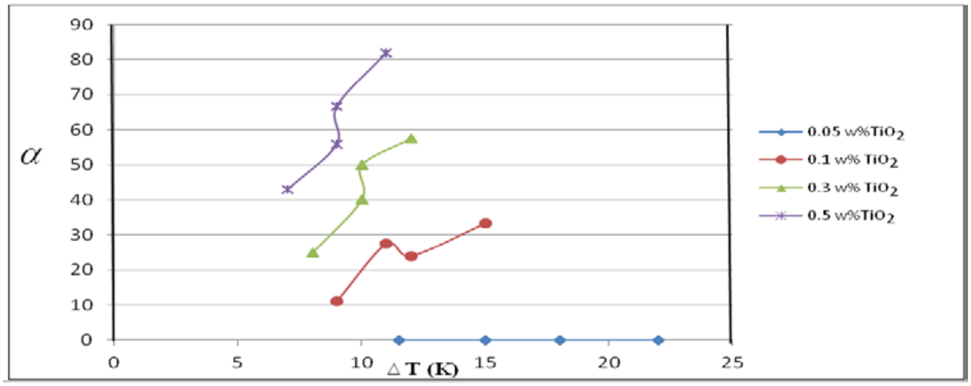


Fig. (19) Heat transfer enhancement of TiO_2 nanofluid with variation in heat fluxes and nanoparticle concentrations

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. Thebest 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.

Nomenclatures

Aarea, m^2
C concentration [v/v]
C_{sf}Surface fluid combination
d_bBubble departure diameter,m
Icurrent, A
K Thermal conductivity, w\m.k
q Heat amount, W
q'' Heat flux W/m^2
T Temperature, K
V Voltage,V
ΔT_{sa}Wall superheat or temperature difference $[T_s – T_{sat}]$ K

Subscripts

$b$bulk
eequilibrium of vapor
$l$liquid
Sat.Saturation
SSurface temperature
$v$vapor

Abbreviation

HTC Heat Transfer Coefficient
HTFs Heat Transfer Fluids
nmnanometer
NfNanofluid
CHF Critical Heat Flux

Greek symbols

αEnhancement of heat transfer coefficient
νKinematic viscosity m^2/s
μDynamic viscosityg/m.s
ρDensity kg/m^3
σSurface tension N/m

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