Al-Khwarizmi Engineering Journal, Vol. 15, No. 1, March, (2019)
P.P. 109- 116

Al-Khwarizmi Engineering Journal

The Effect of Micro and Nano Material on Critical Heat Flux (CHF) Enhancement

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(Received 27 March 2018; accepted 10 June 2018)
https://doi.org/10.22153/kej.2019.06.003

Abstract

The Nano materials play a very important role in the heat transfer enhancement. An experimental investigation has been done to understand the behaviors of nano and micro materials on critical heat flux. Pool boiling experiments have used for several concentrations of nano and micro particles on a 0.4 mm diameter nickel chrome (Ni-Cr) wire heater which is heated electrically at atmospheric pressure. Zinc oxide(ZnO) and silica(SiO_2) were used as a nano and micro fluids with concentrations (0.01,0.05,0.1,0.3,0.5,1 g/L), a marked enhancement in CHF have been shown in the results for nano and micro fluids for different concentrations compared to distilled water. The deposition of the nano particles on the heater surface was the reason behind the enhancement of the wettability of the surface which will increase the CHF, this nano particles deposition will form a porous layer and the mechanism of the formation of this layers is that as vapor bubbles grow, the evaporating liquid in the micro layer leaves behind Nano particles which then will be concentrated at the base of the bubble to form this pours layer. The higher wettability can produce CHF enhancement, the enhancement ratio of Nano fluid is observed to be higher than that of micro fluid, the optimum enhancement ratios of nano fluid is (1 g/l) which observed to be 9.2 % for ZnO and 8.7% for Sio2, and also (1 g/l) for micro fluid which observed to be 8.1%for ZnO and 7.4%for SiO_2.

Keywords: *Critical Heat Flux (CHF), Distilled water, Nano fluids, Pool boiling, (Ni-Cr) wire heater, Nano particles deposited layers.*

1. Introduction

Nano fluids are suspensions of the nano particles in the base fluids with their basic dimensions at the level of the nano scale. Nano particles were Found for promote the physical properties of the nano fluids, such as viscosity, diffusivity, conductivity, to compare it with the essential fluids, such as oil or water [1]. The nano particles may be metal oxides (TiO_2, SiO_2, Al_2O_3, ZnO_2), metallic (Au, Cu), carbon (nanotubes, diamond), or it can be another material. The essential fluids typically have low thermal conductivity, nano particles can be dispersed in the primary liquid and stay suspended in these liquids for a longer period compare with micro size particles. Brownian movement of the nano particles in the essential fluid allows for the nano size particles to stay spread and to improve the thermal properties of the nano fluids. By using small fraction of nano size particles greatly enhances heat transfer capabilities and thermal conductivity of the suspensions without confrontation problems found in common slurries, such as erosion, clogging, sedimentation, and increasing pressure drop [2]. The flow of heat per unit area is called the heat flux, and a temperature difference is the thermodynamic driving force for the flow of the heat [3]. Boiling heat transfer has summit flow of heat below which a boiling surface can remain in the regime of nucleate boiling and represents the maximum heat flux in the curve of boiling which is called CHF, the point after which there is a transition from a nucleate boiling regime to a film boiling regime under pool boiling [4].

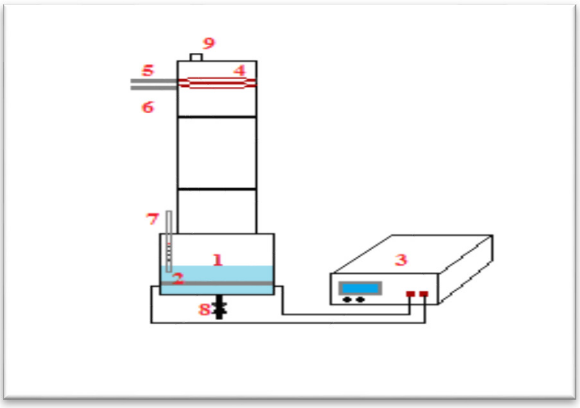
More observations on critical heat enhancement (CHF) were reported by nanoparticles. Vassallo, *et. al.* [5] reported CHF enhancement by using silica water nano fluids in pool boiling pointing to some interaction between the nano particles and the wire heater surface because of the coating of the silica nano particles (0.15 – 0.2) mm that was observed when the experiment was finished . Madhushree, *et. al.* [6] showed enhancement in CHF by using (2.6%) volume fraction of Zinc oxide (ZnO) in ethylene glycol nano fluids. The improvement is related to a pours layer of the nano particles on the surface of the heater wire, the same result is occurred with (Ni-Cr) wire heater for Fe3O4 nano fluids. Milanova and Kumar [7] showed an increased in the CHF at higher pH levels (up to 12.3) when using SiO_2 water nano fluids, but there was a relatively little Effect on the nucleate boiling regime.

Bang, et. al. [8] observed the enhancement in CHF and show that it was due to change in characteristics of the heater surface such as the roughness of the surface and cavities or the intensity of the nucleation site that was affected by the deposition of nano particles. The CHF enhancement that was measure with alumina water nano fluids on a plate heater made from stainless steel and showed that the nano particle porous layers deposit on the heater surface after the boiling of the nano fluids was led to increase the wettability of the surface of the heater. Kim, et. al. [9] reported that a thin layer of nano particles deposition changed the surface energy and morphology and this was closely related to the observed contact angle, activation of the heater surface cavities is discourage by the deposition of the nano particle since there is a reduction in the contact angle, that is lead to reduction in bubble nucleation in nano fluids. The nano particles deposition was observed on the surface of the heater after the nano fluids boiling. The CHF improvement was observed to be of the same amount when both distilled water and nano fluids were boiled on the nano particles deposits heater surface. This means that the modification surface due to the nano particles deposition is the cause behind the improvement in the critical heat flux (CHF), and that may be the working fluid has little effect on the CHF.

2. Experimental Work

The pool boiling vessel that was used for the CHF measurement is made from Perspex glass with (12) cm 1ength (11) cm wide and (16) cm height, this vessel is connected to cylindrical column which contain a copper coil cools by water this coil condenses the generated vapor to minimize the losses in the boiling fluid . Heaters were attached to the boiling vessel in order to maintain the saturation temperature during the experiments for the working fluids. There is a valve, on the top and another one at the bottom which is used as draining. The valve on the top is connected to the condenser to reduce the loss of the working fluid during the boiling experiments. An adjustable heater stand was mounted in the vessel, heater which is made from nickel chrome (Ni-Cr) wire was entered to this stand to estimate the CHF experiments, then connected these wire heaters to the direct current (DC) power supply (LONG WEL, DC POWER SUPPLY PS- 305D), The general pool boiling system with (Ni-Cr) wire heater is show in Fig (1) and the layout of the system is shown schematically in Fig (2). the experiments were carried out in saturated pool boiling under atmospheric pressure.

Fig. 1. Photograph of pool boiling system with Ni-Cr wire heater for CHF measurement.



1 Boiling vessel
2 Heating element(Ni-Cr)wire heater
3 DC power supply for (Ni-Cr) wire to reach maximum heat flux
4 Condenser
5 Condenser cooling water input
6 Condenser cooling water output
7 Thermometer
8 Discharge valve
9 Vent

Fig. 2. Schematic diagram of pool boiling system with Ni-Cr wire heater for CHF measurement.

Before each boiling test of nano fluid, the experiment's vessel is carefully washed by using D.water this ensures that the vessel of the experiment is unpolluted by nano particles from the previous experiment. Then distilled water boiling test is performed and the CHF is calculated and compared to the reference of CHF for distilled water. The experiments were conducted by passing current through the 0.4 mm diameter,100 mm length, Ni-Cr wire heater suspended horizontally first in a distilled water, then nano and micro fluids of ZnO and SiO_2 were used at different concentration [0.01,0.05,0.1,0.3,0.5,1] g/l, these nano and micro particles material were commercially provided, all these experiments have been don under atmospheric pressure. The CHF for distilled water is first calculated by using eq(1), using the data immediately obtained before the sharply increase of the nickel chrome (Ni–Cr) wire resistance.

$$q'' = \frac{VI}{\pi DL} \qquad \ldots(1)$$

Where (**v**) is the inter voltage, (I) is the inter current, (D)represent the wire diameter, and (L) is the length of the wire heater.

The results were compared with The value of CHF calculated by the Zuber's CHF equation [4] which has been used widely to predict the CHF for pure water in pool boiling at 1 atmospheric Pressure eq (2), [10]

$$q'' = C\,\rho_g\,h_{fg}\,[g\sigma(\rho_f - \rho_g)/\rho_g^2]^{1/4} \qquad \ldots(2)$$
$$= 0.131\,h_{fg}\,\rho_g^{1/2}[g\sigma\Delta\rho]^{1/4}$$

Where (q") is the heat flux, (C) constant for many finite heated surfaces, with the value $C = \pi/24 \approx 0.131$ (the Zuber constant) agrees with experimental data, (ρ_g) is the density of gas and (ρ_f) is the density of the fluid, (h_{fg}) is the latent heat of vaporization, (g) is gravitational acceleration, and (σ) is the surface tension [11].

3. Experimental Uncertainty

Considering the uncertainty in calibration, the un certainty in thermometer temperature measurement was ± 0.5 K. The critical heat flux uncertainty in pool boiling is estimated as less than 1%.

4. Results and Discussion

Critical heat flux(CHF) is affected by the addition of the nano and micro particles to the base fluid ,in the experiments we first estimated the value of CHF for distilled water and then for nano and micro fluids , the CHF for distilled water is calculated first by eq(1) after measuring the current and voltage in the experiment that supplied to the Ni-Cr wire immersed in distilled water , the result obtained was compared with the value of CHF calculated from Zuber's CHF equation , eq (2) which has been used widely to predict the CHF value in pool boiling ,the results from Zuber's eq (2)show that the CHF for D. water is agrees well with the value result from eq (1).the numerical values are presented in Table (1). The error ratio between the Predicted and the experiment was 1%.

Table 1,
Critical heat flux values for D. water and physical properties.

Conc (g/l)	CHF W/m^2 Experiment eq(1)		Predicted eq (2)	
D. water	1096337		1106313	
D. water	ρ_g kg/m^3	ρ_f kg/m^3	Surface tension (N/m)	h_{fg} kJ/kg
	0.596	957.9	$58.9*10^{-3}$	2257

Then different concentrations of nano and micro particles of zinc oxide and silica were used to show the effect of these material on critical heat flux. From the experiments and as shown in figure (3),(4) it is observed that the critical heat flux values for the nano and micro fluid increase with increasing the concentration of the particles for both zinc oxide (ZnO) and silica (SiO_2) but the enhancement for the nano fluid is more than that of micro-fluid this is related to the difference in particles sizes that will explain later as shown in figure (5) , the nano and micro particles was stable and suspended in the base fluid and not soluble so the latent heat of vaporization(h_{fg}) and the density of the vapoure (ρ_g) for nano and micro fluids will consider for water only Table (2)and (3)illustrate the results of physical properties and CHF at difference concentration of ZnO and SiO_2 nano and micro fluid .

Table 2,
physical properties and CHF data for ZnO and SiO_2 Nano fluid.

Conc g/l	ρ_f ZnO nanofluid kg/m^3	Surface tension Zno N/m	CHF ZnO Nano W/m^2	ρ_f SiO_2 nanofluid kg/m^3	Surface tension Sio_2 N/m	CHF SiO_2 Nano W/m^2
0.01	1000.5	68.422* 10^{-3}	1160257	1000.5	67.286* 10^{-3}	1156265
0.05	1001	70.546* 10^{-3}	1170169	1001	69.729* 10^{-3}	1166767
0.1	1003	72.932* 10^{-3}	1180529	1003	70.846* 10^{-3}	1171996
0.3	1007	75.818* 10^{-3}	1193226	1007	74.758* 10^{-3}	1189034
0.5	1012	77.948* 10^{-3}	1203009	1012	77.404* 10^{-3}	1200905
1	1017	79.998* 10^{-3}	1212336	1017	78.869* 10^{-3}	1208036

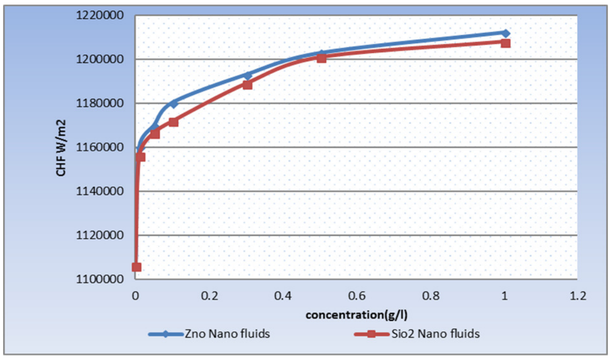


Fig. 3. CHF results for (ZnO, SiO_2) Nano fluid.

Table 3,
physical properties and CHF data for ZnO and SiO_2 micro fluid

Conc g/l	ρ_f ZnO microfluid kg/m^3	Surface tension Zno N/m	CHF ZnO Micro W/m^2	ρ_f Sio_2 nanofluid kg/m^3	Surface tension Sio2 N/m	CHF SiO_2 micro W/m^2
0.01	1000.5	65.378* 10^{-3}	1147980	1000.5	63.611* 10^{-3}	1140143
0.05	1001	67.948* 10^{-3}	1159244	1001	65.936* 10^{-3}	1150565
0.1	1003	70.692* 10^{-3}	1171359	1003	68.324* 10^{-3}	1161324
0.3	1007	72.888* 10^{-3}	1181528	1007	69.356* 10^{-3}	1166946
0.5	1012	74.633* 10^{-3}	1190010	1012	72.473* 10^{-3}	1181305
1	1017	76.766* 10^{-3}	1199902	1017	74.759* 10^{-3}	1191981

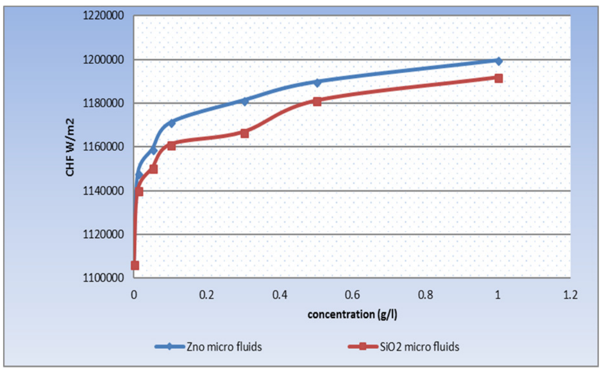


Fig. 4. CHF results for (ZnO, SiO_2) micr0 fluid.

5. The Effect of ZnO and SiO_2 Deposition on Heater

The ZnO and SiO_2 nano particle depositions which are results during the boiling of the nano fluids will form porous layers on the heater surface and will effect on the heater properties such as morphology, contact angle and wettability. The nano particles deposit layer on the nickel chrome (Ni–Cr) wire can improve the wettability of the wire heater, this wetting capability enhances the CHF of the nano fluids, as the amount of the nano particles deposition increased the CHF improvement will also increase. Therefore, at higher nano particles deposited concentrations the CHF was more enhanced, so, the surface wettability, which is important parameter for enhancement of the CHF, is changed and the CHF is also enhanced for both nano and micro fluids.

The AFM test for Zinc oxide, silica nano and micro-particles was found to show the particle size distribution of these particles that have an effect on improving critical heat flux, and their elevation is that the average ZnO nano particles is equal to (57.01) nm less than the silica nanoparticles (69.74) nm, and found that of Zinc oxide micro particles is(896.81) nm which is less than that of Silica micro particles (1017.96)as shown in Fig (5),

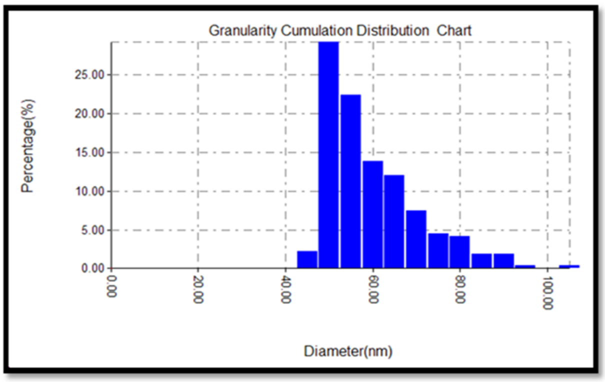


Fig. 5-a. Bar chart of particle size distribution of ZnO nanoparticles.

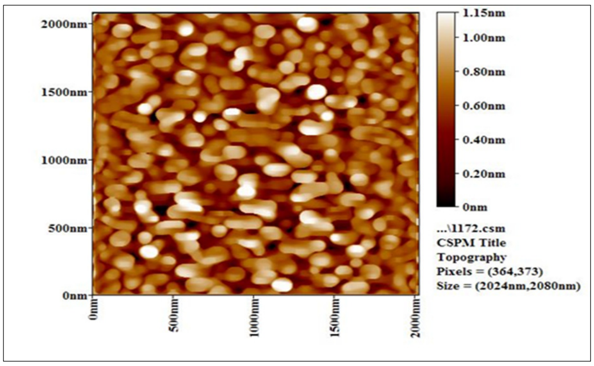


Fig. 5-a1. AFM for ZnO Nano particles with average diameter of (57.01) nm.

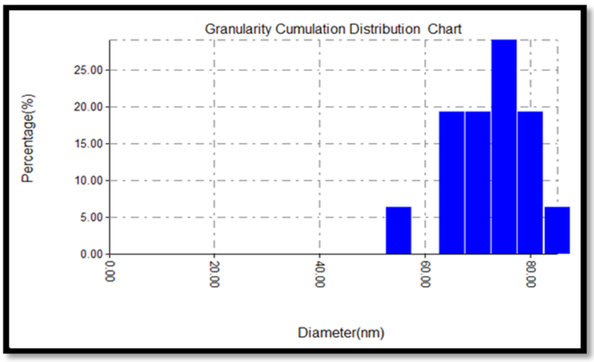


Fig. 5-b. Bar chart of particle size distribution of silica nanoparticles.

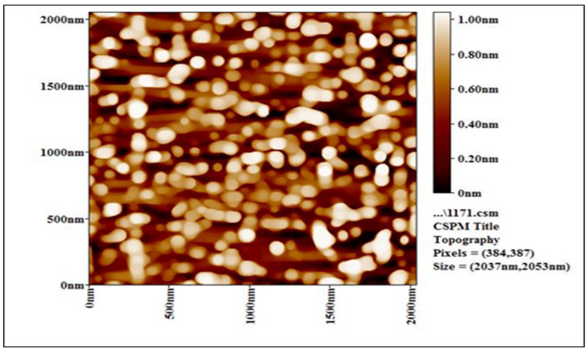


Fig. 5-b1. AFM for SiO_2Nano particles with average diameter of (69.74) nm.

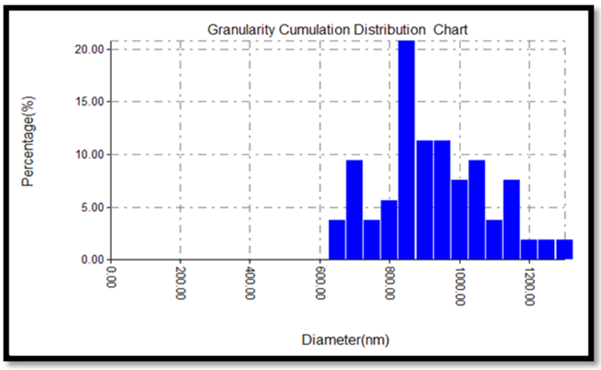


Fig. 5-c. Bar chart of particle size distribution of ZnO micro particles.

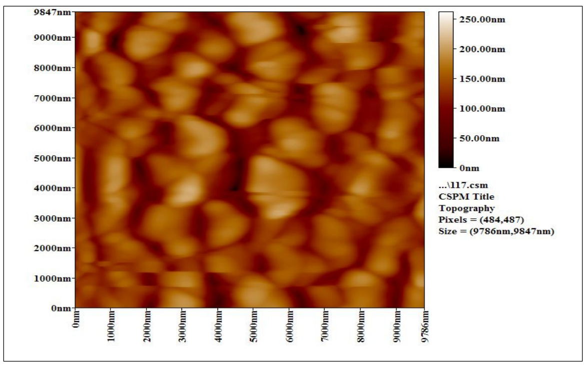


Fig. 5-c1. AFM for ZnO micro particles with average diameter of (896.81) nm.

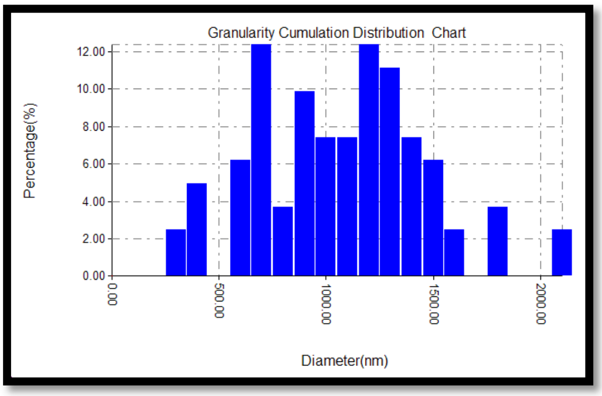


Fig. 5-d. Bar chart of particle size distribution of silica micro particles.

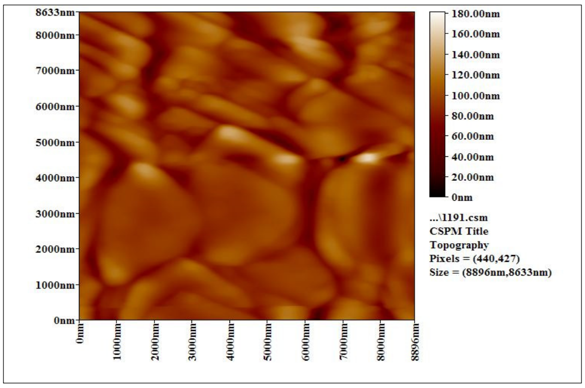


Fig. 5-d1. AFM for SiO_2micro particles with average diameter of (1017.96) nm.

Fig. 5. AFM for zinc oxide and silica Nano and Micro particles.

As shown in Fig (6), CHF for the ZnO nano fluid is higher than the ZnO micro fluids, and the SiO_2 nano fluids are also higher than the SiO_2 micro fluids. This is related to the difference in particle size as shown in Fig (5). When the particle size is small in nanometers scale, it will be better to improve the CHF than when the particle size is in large size particles or micro particles. This is because nano particles will spread more widely on the surface of the heater and this will increase the surface area of the heat transfer compare to micro fluids. And this is why nano materials improves more than micro materials. If we compare the improvement in CHF between the ZnO and SiO_2 nano particles themselves, it was found that ZnO nanoparticles will occurs higher enhancement than silica nano particles, this may be related to the nature of the material itself in heat transfer and also related to the particle size of nano particles.

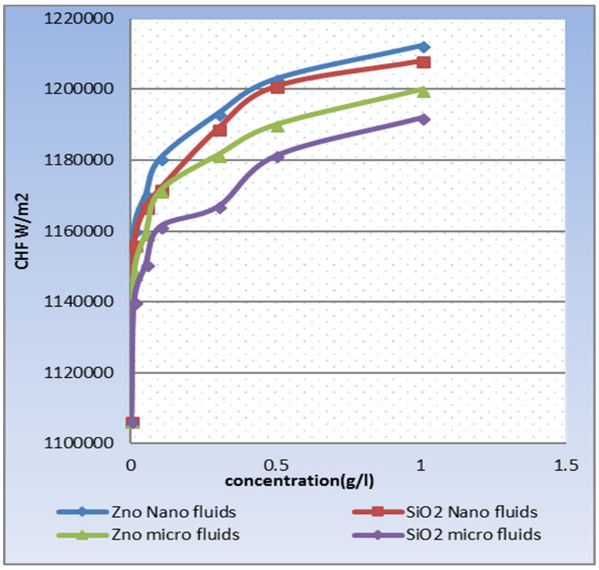


Fig. 6. comparison of CHF between (ZnO, SiO2) Nano and micr0-fluid.

During the boiling of the nano fluid, the nano particles deposition will be formed on the heater surface, when the number of bubbles increases, the vapor of the liquid is also increase, leaving nano particles behind it, which is then focus on the heater surface to form this porous layer. Presence of this porous layer pointing to change of the surface heater wire morphology, the nano particles deposit layer on the nickel chrome (Ni–Cr) wire can enhance the wettability of the wire heater, this wetting capability enhances the CHF of the nano fluids, when the nano particles deposition amount increased the CHF improvement will also increase. So, at higher nano particles deposited concentrations the CHF was more enhanced**,** therefore, the surface wettability, which is important parameter for enhancement of the CHF, is changed and the CHF is also enhanced for both nano and micro fluids.

6. Conclusion

The characteristics of CHF improvement by using Zinc oxide (ZnO), and silica (SiO_2) nano and micro fluids are investigated experimentally in this study, the main findings are as follows:

- There is a similarity in Critical heat flux values for D. water between the theoretical and experimental result.
- The CHF increase with increasing nano and also micro particle concentration but the enhancement for nano particles was more than micro particles.

- The optimum enhancement ratios for nano fluid is (1 g/l) which observed to be 9.2 % for ZnO and 8.7% for SiO2 and also (1 g/l) for micro fluid which observed to be 8.1% for ZnO and 7.4%for SiO2.

Nomenclature

Symbol	**Description**	**Unit**
CHF	Critical Heat Flux	W/m^2
g	Gravitational Acceleration	m/s^2
q”	Heat Flux	W/m^2
ρ_g	The Gas Density	kg/m^3
ρ_f	The Fluid Density	kg/m^3
h_{fg}	The Latent Heat of Vaporization	
σ	The Surface Tension	N/m
V	The Inter Voltage	volt
I	The Inter Current	Amp
D	The Diameter of the Wire heater	m
L	The Length of the Wire heater	m

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تأثير المواد المايكروية والنانوية على تحسين تدفق الحرارة الحرجة

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الخلاصة

تؤدي المواد النانوية دورا مهما في تحسين انتقال الحرارة، وقد تم اجراء بحث تجريبي لفهم سلوكية المواد النانوية والمايكروية وتاثيرها على تدفق الحرارة الحرجة، تم اجراء هذه التجارب بوساطة استخدام سلك ذي معدن (Ni-Cr) قطره (0.4) ملم عند الضغط الجوي، تم استخدام اوكسيد الزنك والسليكا بوصفها سوائل نانوية ومايكروية بتراكيز (0.01,0.05,0.1,0.3,0.5,1)غم/ لتر وقد اشارت نتائج هذه التجارب الى زيادة تحسين ملحوظ في تدفق الحرارة الحرجة لكل من السوائل النانوية والمايكروية لهذه التراكيز مقارنة مع الماء المقطر، ويرجع سبب هذا التحسين الى ترسب الجسمات النانوية على سطح المسخن الذي يؤدي الى تكوين طبقة مسامية على سطح المسخن وتؤدي هذه الطبقة الى زيادة قابلية سطح المسخن للبلل والتي تزيد من تدفق الحرارة الحرجة، ان ميكانيكية تكون هذه الطبقة المسامية على سطح المسخن يرجع الى انه خلال عملية غليان السوائل النانوية وظهور الفقاعات سوف يزداد بخار السائل مما يودي الى ترسب المواد النانوية على السطح بعد تبخر السائل مكونة هذه الطبقة حيث تعمل على تحسين قابلية سطح المسخن الى حد كبير، وقد وجد ان نسبة التحسين الامثل لاوكسيد الزنك عند استخدام (١غم/لتر) هي٩,٢% و٨,٧% للسيليكا للسوائل النانوية، وايضا (١ غم/ لتر) للسوائل المايكروية التي لوحظت ان تكون ٨,١% لأوكسيد الزنك و٧,٤% للسيليكا.