Experimental Investigation of Pool Boiling of Single Wall Carbon Nanotubes (SWCNTs) with Different Grooved Surfaces

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Abstract: The enhancements in boiling heat transfer can bring immediate benefits to improve the efficiency and cost of heat energy transfer. In this study, heat transfer coefficient in pool boiling of single wall carbon nanotube-water (SWCNTs) at a concentration of 0. 05, 0. 1 and 0. 15 vol. % on smooth and grooved surfaces has been investigated experimentally at atmospheric pressure. The effect of some shapes namely circular groove, square groove and straight groove on the boiling heat transfer has been also investigated. The experimental results indicated that making different grooved surfaces and also using (SWCNTs)-water enhanced the boiling heat transfer coefficient. The highest increase in heat transfer coefficient was seen in circular grooved, which is 76% higher than the base fluid water on the smooth surface. The heat flux has been changed from 0 to 140 kW/m^2. By comparing the results, the circular groove with 0.15% concentration of SWCNTs has higher heat transfer coefficient for the boiling heat transfer. Based on pool boiling surfaces, a new type of grooves pool pooling surface was designed and constructed, which is consisted of inclined circular groove at angle of 45°. Outcome of the present work definitely indicates that the inclination of the circular groove could be excellent option for the increasing of pool boiling heat transfer. Cornwel-Houston correlation has been modified to take care of the effect of grooved surfaces for correlating the Nusselt number as a function of Reynolds number and Prandtl number in pool boiling. This new correlation agrees with the experimental data from the augmented surface satisfactory.

Keywords: Grooved Surface, Heat Transfer Coefficient, Pool Boiling, Pool Boiling, Single Wall Carbon Nanotube

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1 INTRODUCTION

Augmentation of pool boiling is one of challenging fields of research in heat transfer for many years. To enhance the heat flux, numerous techniques were applied such as increasing the surface area of boiling and using nano and etc. At pool boiling, heat is transferred by combination of two mechanisms. At the first mechanism, bubbles are formed at nucleation cavities on the heated surface and as the result; the heat is transferred by nucleate boiling mechanism. In the second way of heat transfer, heat is transferred from the wall to the liquid film by convection and goes into the bulk liquid or causes evaporation at the liquid–vapour interface. In the first mechanism surface condition is important and in second mechanism the effect of nano particles is important.

Reviewing the literature makes it clear that although many investigators have considered different types of surfaces and nanofluids in pool, no study has qualitatively described the boiling behavior with detailed characterizations of smooth and groove surfaces and use of SWCNTs.

The aim of present study is to compare heat transfer coefficient of a new type of grooved surface under pool boiling and the same time using SWCNTs. In this study, a new type of boiling heat transfer surface is designed and constructed which is consisted of circular grooved. Then, some experimental tests were carried out to compare the thermal performances of four kinds of surfaces with SWCNTs. The outcomes of this research can be beneficial for engineers whom work on pool boiling systems.

2 LITERATURE REVIEW

Boiling heat transfer involves in many engineering applications associated with high heat fluxes. There are numerous investigations in the past decades, in order to study the enhancement of boiling heat transfer by using nano. In the past three decades most of investigators worked on pool boiling using Al_2O_3 [1-7] but the problem of using Al_2O_3 is apparently these nanoparticles in agglomerated form were located in the large cavities and multiplied the cavities by splitting a single nucleation site into multiple one and they have also low thermal conductivity [8].

Also some others investigators examined CuO as a nanofluid for pool boiling. Some experimental study has been done by [9- 11] on CuO through pool boiling heat transfer with various concentration nanoparticles. The results showed enhancement in boiling heat transfer coefficient but CuO has the same problems with Al_2O_3. Pool boiling heat transfer behaviour of TiO_2 in pure water has been recently investigated by [12-14] and also multi- wall carbon nanotubes (MCNTs) suspension in pure water has been investigated [15-16]. They found that the heat transfer coefficient of the base mixture (MWCNT –water) has been enhanced by adding of nanoparticles.

Also extensive studies have been made in the past decades, in order to study the enhancement of boiling heat transfer by using different surfaces [17–22]. Pool boiling heat transfer on horizontal metallic foam surface with crossing and single-directional V shaped groove was experimentally investigated by Qu et al. [20] at atmospheric pressure using deionized saturated water at the working liquid. They found that the effect of groove number was heavily dependent on foam thickness. An experimental investigation of pool boiling heat transfer on smooth/rib surfaces under an electric field is studied by Quan et al. [21]. They found that the ribs on a heating surface can change the distribution of electric field strength and also affect the growth of bubble.

Das et al [22] experimentally showed the tunnels inclined in pool boiling surface at an angle 60° with the horizontal provide better augmentation compared to straight vertical tunnels. They found that also the use of tunnel also increases the degree of augmentation.

Heat transfer from plain surface and from surfaces with distinct nucleation sites has been investigated by Das et. al [23] under saturated pool boiling condition. Surfaces have been prepared with regular array of discrete nucleation sites formed by micro- drilling. Some modification has been developed and used to predict the experimental data from augmented surfaces. Reviewing the literature makes it clear that although many papers have considered different types of heat transfer surfaces and investigated various aspects of it, aluminium surfaces are the more common and mainstream choice because of their simple geometry and well thermal performance. As a result, having a superior performance is not the only consideration in manufacture of practical heat transfer surface, but a simple geometry is also considered a merit along with low cost of manufacturing. Although a few numbers of grooved surfaces have been commercially marketed for the increasing of boiling heat transfer coefficient, reviewing the literature makes it clear that the mechanism of boiling in groove surfaces with nanofluid especially single carbon nanotube-water nano (SWCNTs) is not investigated.

3 EXPERIMENTAL APPARATUS AND UNCERTAINTIES

Rough surfaces under typically have quite complex surface geometries, for which the heat transfer coefficient, h, cannot be analytically predicted. Since manufacturers treat such data as proprietary, the h relation should be derived from test data which are specific to the surface geometry [24].

Experimental setup which consists of a cylindrical boiling vessel is shown in "Fig. 1". The glass cylinder has been used to observe bubble dynamics for pool boiling.

In the experimental setup, various instruments were used to measure temperature at different points. A coil heater of 1000W for initial heating has been used during the experiments to provide Dirichlet boundary condition. Insulation of the bottom side of the heater is done perfectly by means of a guard heater to guarantee complete heat transfer to the pool boiling surface.

The condenser with diameter of 90mm and length of 320mm at the top is connected directly to the test section for cooling of any vapour which may try to escape as well as act as a vent to non-condensable gasses. The cooling water is then circulated through a stainless steel tube with diameter of 3mm and length of 200mm.

A voltmeter-ammeter is used to monitor the current flow and voltage drop of the system in order to calculate the supplied power (supplied power=heater current × voltage drop). Temperature difference is considered to be negligible and steady state condition is supposed to be reached, when the recorded temperature difference of each thermocouple becomes less than 0.5 °C/hour. All the observations are recorded after confirmation of steady state condition.

Fig. 1 The experimental setup.

The experimental apparatus for the heat transfer experiments consisted of the experimental condenser (1), Pyrex glass (2), boiling liquid (3), test plate (4), Varic (5) heater (6), thermometer (7), thermocouples (8) and retained plate has been shown in "Fig. 2".

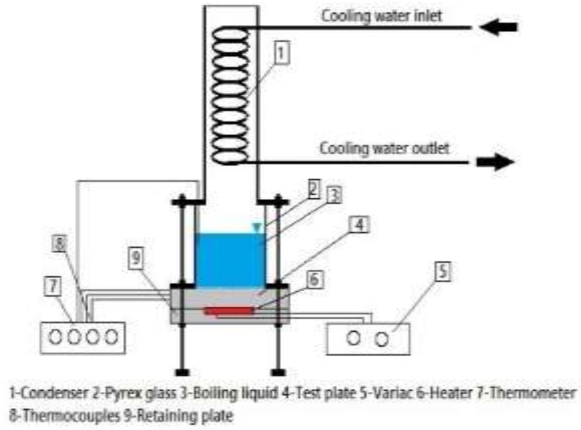

Fig. 2 Schematic of the experimental setup.

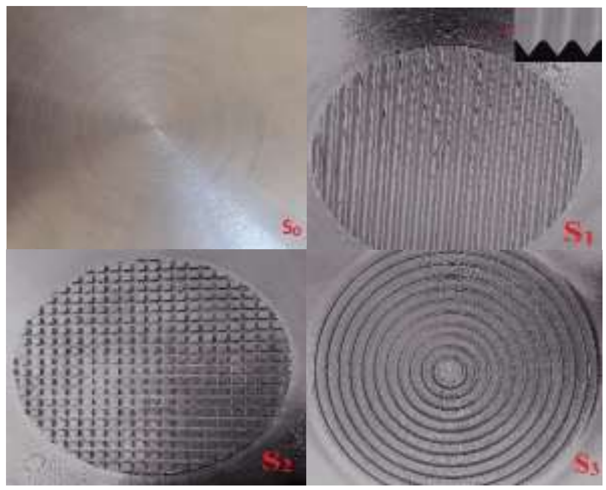

Fig. 3 Various surfaces including smooth (S0) and grooved surfaces (S1, S2, S3).

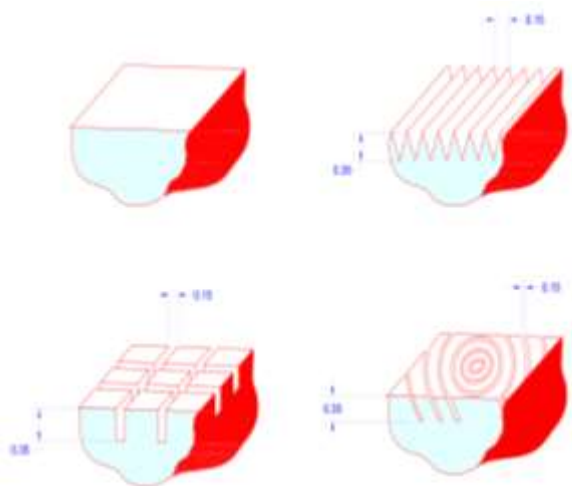

Fig. 4 Schematic of smooth (S0) and grooved surfaces (S1, S2, S3).

In this study the heat input has been varied by changing the voltage with the help of voltage regulator. The cylindrical boiling vessel (2), made up of 100 mm diameter Pyrex glass and height of 190 mm, stores the water for pool boiling. As it has been shown in “Fig. 3” and “Fig. 4”, for aluminium sheets with thermal conductivity of 140 W/m. K has been used in this experimental.
The surface conditions are an important factor in pool boiling. As the result, three different shapes of groove have been made to examine their efficiency in pool boiling with and without nanofluids. The pictorial view of four representative surfaces is shown in “Fig. 3”, and geometrical details of the surfaces are schematically shown in “Fig. 4”.

4 PREPARATION OF NANOFLUIDS

In this study, nanofluids with 0.05%, 0.1% and 0.15% concentrations of single wall nano carbon tube (SWCNTs) nanoparticles in water has been examined and the TEM images of the single wall nano carbon tube (SWCNTs) has been shown in “Fig. 5”. The Physical properties of single wall carbon nano tubes (SWCNTs) have been listed in “Table 1”.

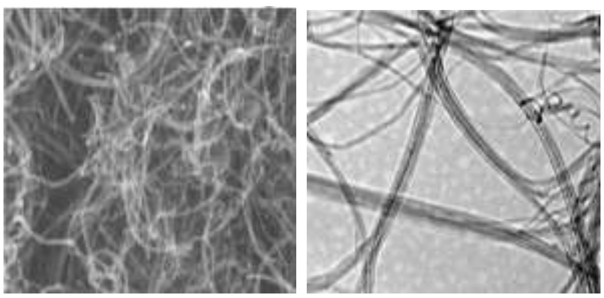

Fig. 5 SEM and TEM images of the single wall nano carbon tube (SWCNTs).

Table 1 Physical properties of single wall carbon nano tubes(SWCNTs)

Material	SWCNT
Young’s modulus (GPa)	1054
Tensile Strength (GPa)	150
Density (g/cm^3)	2.1
Thermal Conductivity W/m .K	3000
Electrical Conductivity S/m	10^5 -10^7

The preparation of nanofluids aim to make nanoparticles suspend in base fluids with stability, without sedimentation [19]. In this study, to prepare SWCNTs/water, after magnetic stirring for 3 hours, the suspensions were exposed to an ultrasonic processor with power of 600W. This method, which leads to attain a stable suspension and a uniform dispersion, was used in order to break down the agglomeration between the particles (see “Fig. 6”). The Physical properties of single wall carbon nanotubes is shown in “Table1”.

Fig. 6 Photograph of SWCNTs and functionalized SWCNTs/water.

5 DATA PROCESSING

There are two methods to obtain the heat flux. The first one is to use the heat power over heating area by the following equation:

$$q" = \frac{IV}{A} \quad (1)$$

In this equation I is the current (Amps), V is the voltage (Volts), and A is the heating surface area (m^2) which can be calculated from A = πDL and D is the diameter of the heater cylinder.

Fig. 7 (a): Experimental setup of the surface and (B): Boiling surface with three thermocouples embedded inside it.

The second method is that the heat conducted inside the heater is in one dimensional and the heat flux can be obtained from the tested temperatures T_1, T_2, and T_3 which is shown in “Fig. 7”. Thermocouples T_1, T_2 and T_3 are connected to the surface directly so the wall temperature could be measured with more accuracy. The authors used the second method to calculate the heat flux to reduce the effect of heat loss on heat transfer performance. Boiling surface with three thermocouples embedded inside it. The heat flux of the heater was obtained from the one-dimension heat conduction and is expressed as:

$$q = k_s \frac{dT}{dz} |_W \quad (2)$$

Where k_s is the aluminium thermal conductivity, dT_w is the temperature gradient on the heater upper side, and z is the coordinate perpendicular to the substrate surface.

$$q'' = k\ \frac{\partial T}{\partial x}\ = k\ \frac{(T_3 - T_1)}{2x} \tag{3}$$

Where k=140 W/m. K and x= 7mm. As the results, the boiling heat transfer coefficient can be calculated as follows:

$$h = q/(T_W - T_S\ ) \tag{4}$$

Where T_s, is the saturation temperature of boiling water at atmospheric pressure and T_w are mean wall temperature. Now by using “Eq. (2)” we can calculate the surface temperature:

$$T_W\ =\ T_1\ -\ q''\left(\frac{L}{k}\right) \tag{5}$$

The detailed experimental procedures and data reduction and uncertainty analyses can be found in Moffats study [25]. The relative uncertainty of the heat flux and heat transfer coefficient can be calculated by the function:

$$q'' = f(\Delta T, \Delta x)$$
$$\frac{U_{q''}}{q''}\ =\ (\left(\frac{U_{T_3-T_1}}{T_3-T_1}\right)^2\ +\left(\frac{U_{X_3-X_1}}{X_3-X_1}\right)^2)^{0.5} \tag{6}$$

$$T_W = f(L, q")$$
$$\frac{U_{q''}}{q''} = (\left(\frac{U_{T_1-T_{sat}}}{T_1-T_{sat}}\right)^2\ +\left(\frac{U_L}{L}\right)^2)^{0.5} \tag{7}$$

$$h = f(\Delta L, q")$$
$$\frac{U_h}{h} = (\left(\frac{U_{q''}}{q''}\right)^2\ +\left(\frac{U_{\Delta T_S}}{\Delta T_S}\right)^2)^{0.5} \tag{8}$$

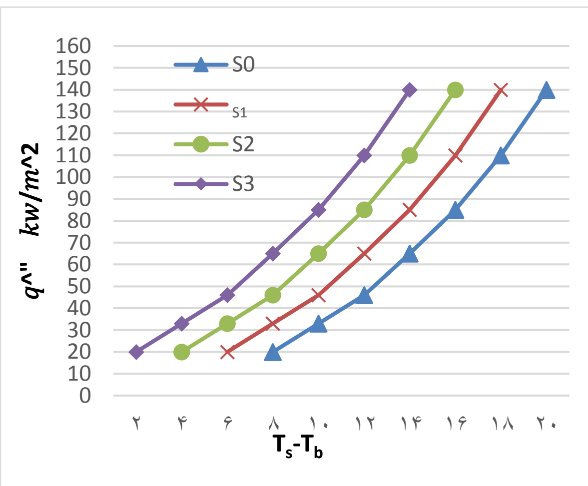

Fig. 8 Boiling heat flux vs differences temperature for pure water for S0, S1, S2 and S3.

6 RESULTS AND DISCUSSION

The analysis of nucleate boiling requires prediction of the number of surface nucleation sites and the rate at which bubbles originate from each site. The influence of surface roughness by grooving on the film boiling cannot be neglected. However, as demonstrated by [19], [26], [27], increased surface roughness can cause a large increase in heat flux for the nucleate boiling regime.

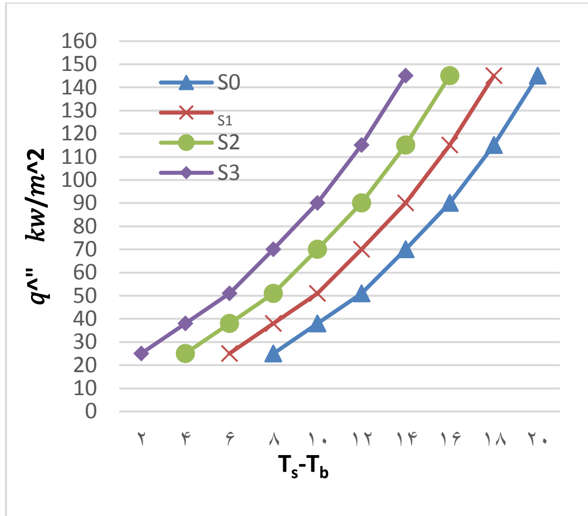

Fig. 9 Boiling heat flux vs differences temperature for SWCNTs with 0. 05% concentration for S0, S1, S2 and S3.

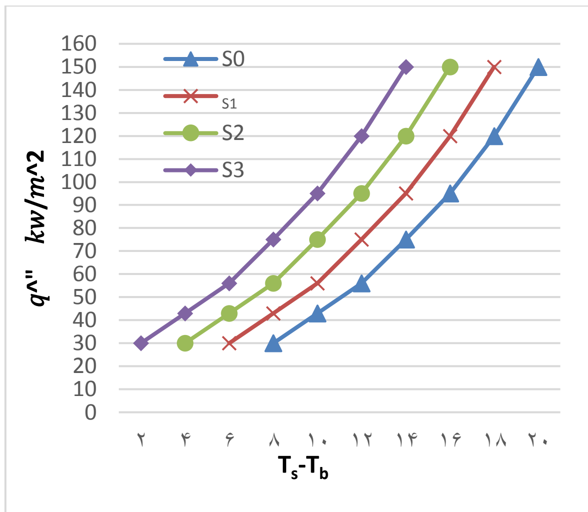

Fig. 10 Boiling heat flux vs differences temperature for SWCNTs with 0.1% concentrations for S0, S1, S2 and S3.

In order to more study on effect of surface features on boiling characteristics, a new series of experiments were series in this paper and also the aim of this novel study is to compare the boiling heat transfer coefficient of four surfaces using SWCNTs with different concentrations with difference surfaces. The boiling heat flux of SWCNT /water nanofluid versus the difference temperature is illustrated in “Fig. 8”.

The presence of nanoparticles is seen to reduce the surface temperature significantly and the wall temperature reduction not only increases with increasing heat flux but also increases with increasing nanoparticles concentration. “Fig. 9”, shows boiling heat flux us differences temperature for SWCNTs with 0. 05% concentration for S0, S1, S2 and S3. Also, “Fig. 10”, shows boiling heat flux vs differences temperature for SWCNTs with 0.1% concentration for S0, S1, S2 and S3.

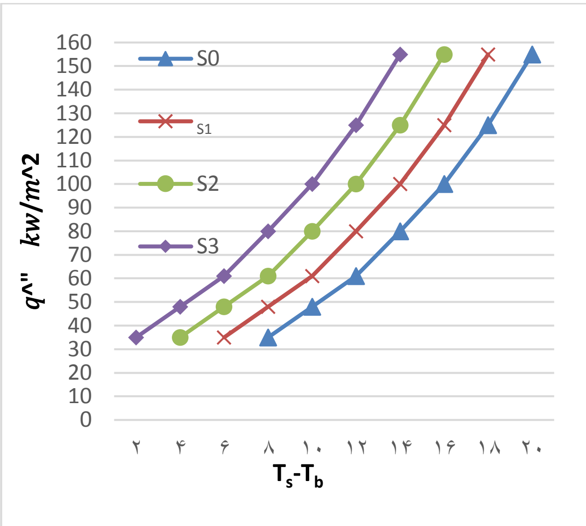

Fig. 11 Boiling heat flux vs differences temperature for SWCNTs with 0.15% concentration for S0, S1, S2 and S3.

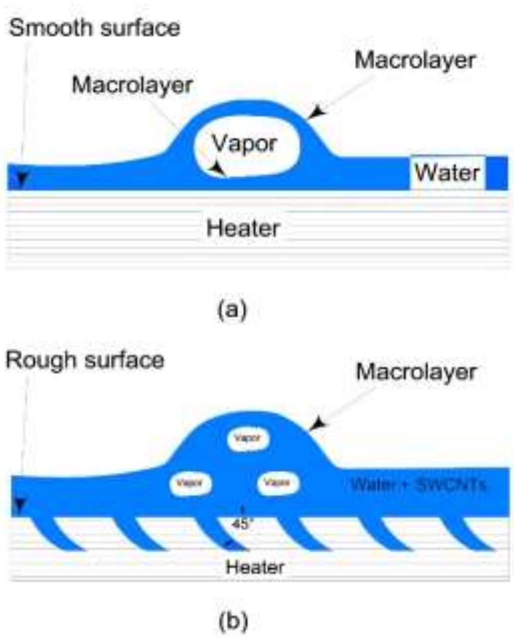

Fig. 12 Schematic of hypothesis for water film structure in pool boiling: (a): with smooth surface and (b): new illustration for vapors formation with groove surface (S3) and nano.

“Fig. 11”, shows boiling heat flux vs differences temperature for SWCNTs with 0.15% concentration for S0, S1, S2 and S3. It is expected that these grooves will serve two purposes. Firstly, they will provide a larger groove area. Secondly, they will also establish a square network for the transportation of liquid and vapor. The possibility of movement on a large two dimensional plane from any point of this network definitely provides a better scope for the transport of thermal energy.

As “Fig. 12a” and “Fig. 12b”, illustrate that a roughened surface has numerous cavities that serve to trap vapor, providing more and large sites for bubble growth. By using grooved surface especially inclined circular groove at angle of 45°and the presence of nanoparticles, the collision between the heating surface and the particles increases, creating more bubbles and as a result, higher heat transfer coefficients. This is very good achievement in pool boiling and to the best of the knowledge of the authors this has not been reported earlier.

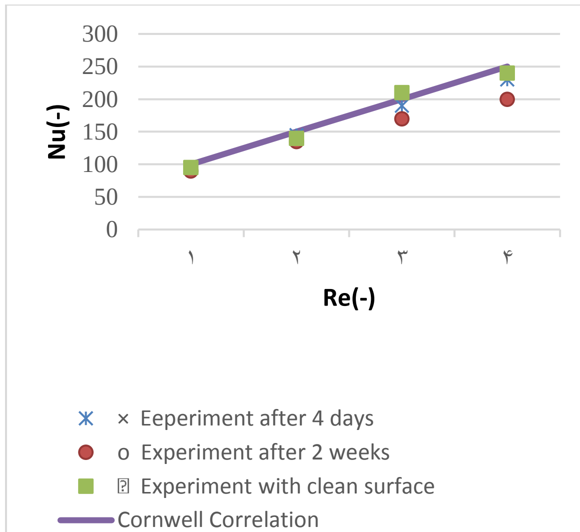

Fig. 13 Comparison of boiling of pure water in the present set- up with Cornwell- Houston correlation [21].

As shown in “Fig. 13”, the $Nu - Re_b$ data of different runs for S0 and S1 and S3 and S4 surfaces is plotted. $Nu = hD/k$ is the usual Nusselt number and $Re_b = q''D/(h_{fg}\mu_f)$ is the boiling Reynolds number [28]. Further the convective type correlation of Cornwell and Houston [28] is plotted in the same figure. The plot shows good agreement of “Eq. (9)” and it also shows that heat transfer coefficient increases in surface S1 and S2 and S3 due to shape of grooved surfaces, respectively.

$$Nu = 104Re_b^{0.67}Pr^{0.4} \tag{9}$$

Following the above validation, experiments were carried out to evaluate pool boiling with single wall carbon nanotube-water (SWCNTs) at a concentration of 0. 05% and 0. 1% and 0. 15%. The following correlations were obtained for pure water with smooth and grooved surfaces without and with nano. According to "Eq. (9)" the exponent of Pr is taken at 0.4.

Pure water	**Equation**
For surface S0	Nu =83$Re^{0.76}Pr^{0.4}$
For surface S1	Nu =87$Re^{0.76}Pr^{0.4}$
For surface S2	Nu =91$Re^{0.76}Pr^{0.4}$
For surface S3	Nu =98$Re^{0.76}Pr^{0.4}$

SWCNTs 0.15%	**Equation**
For surface S0	Nu =125$Re^{0.76}Pr^{0.4}$
For surface S1	Nu = 131$Re^{0.76}Pr^{0.4}$
For surface S2	Nu = 136$Re^{0.76}Pr^{0.4}$
For surface S30	Nu = 146$Re^{0.76}Pr^{0.4}$

7 CONCLUSION

A series of new experimental study were performed to measure the heat transfer rate of the grooves surfaces under pool boiling in the presence of the single wall nano carbon tube(SWCNTs) nanoparticles in different concentrations (0.05%, 0.1% and 0.15%). Based on pool boiling surfaces, a new type of grooves pool pooling surface was designed and constructed, which is consisted of inclined circular groove. After that, some experiments were carried out to compare the thermal performance of different types of pool boiling surfaces. The experimental results exhibited that heat transfer coefficient was about 12% higher than that of smooth surface. From the experimental results and discussion on the performance characteristic of four surfaces arrangement in pool boiling, the following conclusions may be drawn:

1. Making different grooved surfaces enhanced the boiling heat transfer coefficient and the highest increase in heat transfer coefficient was seen in circular grooved, which is 76% higher than the base fluid water on the smooth surface.
2. By comparing the results, the circular groove with 0.15% concentration of SWCNTs has higher heat transfer coefficient for the boiling heat transfer.
3. By using grooved surface especially inclined circular groove at angle of 45° (in our case S3) and the presence of nanoparticles, the collision between the heating surface and the particles increase, creating more bubbles and as a result, higher heat transfer coefficients.
4. Outcome of the present work definitely indicates that the inclination of the circular groove could be excellent option for the increasing of pool boiling heat transfer.
5. Cornwell -Houston correlation has been modified to take care of the effect of grooved surfaces in pool boiling. This correlation agrees with the experimental data from the augmented surface satisfactory.

NOMENCLATURE

h	Convection heat transfer coefficient	$W/m^2.K$
L	Distance between thermocouple and surface	mm
"q	Heat flux	W/m^2
q	Heat transfer rate	W
T	Temperature	K
k	Thermal conductivity	W/m. K
x	Position of thermocouple	mm
u	Uncertainty	(-)
V	Voltage	V
I	Current	A
ΔT	Temperature difference	K
A	Area of boiling surface	m^2
h	Latent heat of phase change	J/kg

Greek symbols

μ	Viscosity	kg/m. s
Δ	Difference	

Subscripts

f	Fluid
g	Glass
sat	Saturation
w	Boiling surface

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