Experimental investigation of Multiwall Carbon Nanotubes/Water Nanofluid Pool Boiling on Smooth and Groove Surfaces

Amir Vasei Moghadam[1], Hamid Reza Goshayeshi*[1], Issa Chaer[2], Alex Paurine[2], Saeed Zeinali Heris[3,*]

[1]Department of Mechanical Engineering, Azad University, Mashhad Branch, Mashhad, Iran
[2] Centre for Civil and Building Services Engineering, School of the Built Environment and Architecture, London South Bank University, London, SE1 0AA UK

[3]Faculty of Chemical and Petroleum Engineering, University of Tabriz, Tabriz, Iran

Abstract

Boiling is an essential process for many industrial applications such as refrigeration, distillation, chemical processes. The efficiencies of these applications are dependent on effectiveness of the heat transfer processes. This study presents the experimental data analysis for pool boiling performance of 0.10~0.20% (wt%) of Multiwall Carbon Nanotubes (MWCNTs)/water nanofluid on smooth and straight, square and circular grooved surfaces. According to experimental results, the highest enhancement in boiling heat transfer coefficient is observed in configuration S4 consisting of 30mm deep circular groove inclined at 45° angle and 33% higher than the base fluid on the smooth surface. Based on this investigation, the paper indicates that the inclination of the circular groove has the potential to enhance significantly pool boiling heat transfer process. Furthermore, the paper justifies that the effectiveness enhancement analysis of the nanofluids under a range of concentrations and geometrical configurations of heat transfer surfaces is still essential and desirable.

Keywords: Nanofluid; Heat transfer enhancement; Pool boiling; Multiwall Carbon Nanotubes; Grooved surface.

---

* Corresponding author email: s.zeinali@tabrizu.ac.ir, goshayshi@yahoo.com

Tel: (+98) (41) 33392412

Fax: (+98) (41) 33338497

Nomenclatures

A	area of boiling surface (m^2)
C	heat capacity (J/kg K)
D	diameter (mm)
L	distance between thermocouple and surface and heater length (mm)
h	convection heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
q''	heat flux (W/m^2)
q	rate of heat transfer (W)
T	temperature (K)
k	thermal conductivity (W/m K)
n	number of surfaces
x	position of thermocouple (mm)
U	uncertainty -
V	voltage (V)
I	current (A)
ΔT	temperature difference (K)
R_a	Roughness value (mμ)
Greek symbols	
$\boldsymbol{\mu}$	viscosity (kg/m s)
ρ	density (kg/m^3)
φ	volume concentration
Δ	difference
Subscripts	
f	fluid
l	liquid

p	particle
sat	saturation
w	water

1. Introduction

Boiling heat transfer is involved in many engineering applications associated with high heat fluxes. So many researchers looked into the enhancement of boiling heat transfer by using Nano-technology in the past decades. In the past three decades, most of the investigators worked on pool boiling using Al_2O_3 nanoparticles Kwark et al. [2010] & Ham et al. [2014] & Karimipour [2015].

Nucleate pool boiling of Al_2O_3 based aqueous nanofluid on flat plate heater has been studied experimentally by Shahmorad et al. [2013]. Their investigation showed after boiling of nanofluid the surface roughness increases or decreases depending on initial condition of heater surface and they reported changes in boiling surface topology during different regions of boiling, wettability and thermal resistance of heater surface owing to nanoparticles deposition caused to variations in nanofluids boiling performance.

Also, others investigators examined CuO as nanoparticles for pool boiling. Some experimental studies were conducted by Mirziei M [2017] & El-Khouly et al. [2021] on pool boiling heat transfer with a range of CuO nanoparticles concentrations. CuO has similar issues as those of Al_2O_3 nanoparticles, the results indicate the rise in Nusselt number Dadjoo et al. [2017] & Arenales et al. [2020].

Sarafraz et al. [2020] investigated the heat transfer coefficient (HTC) of Fe_3O_4 aqueous nano-suspension at various mass concentrations of 0.05% 0.2%. The potential role of operating parameters including heat flux perpendicular to the surface, concentration of the nanoparticle, strength of magnetic field (MF), zeta potential and concentration of a specific surfactant on

HTC, critical heat flux (CHF) and transient fouling resistance of the surface was identified. Results showed that MF can lower the fouling resistance providing that the nano suspension is stable. It was shown that in this case, the HTC value was also promoted.

Xu et al. [2021] studied, bubble growth on the boiling surfaces and pool boiling heat transfer characteristics of semi modified pillar arrays are experimentally investigated at atmospheric pressure, deionized water, aqueous isopropanol and n-heptanol solutions with concentrations were used as the working liquids. The experimental results show that contact angles of isopropanol and n-heptanol solutions on copper plate are changed considerably by silver-deposition.

The coefficient of heat transfer for the behavior of TiO_2 nanoparticles in pure water has been recently studied by Salimpour et al. [2015] & Mahmoudi et al. [2017]. In a pool boiling regime, heat is transferred by two distinct mechanisms. Firstly, bubbles are generated at nucleation cavities. Secondly, by convection from wall heat is transferred into the bulk liquid. In the first mechanism, the surface condition is important whereas in second mechanism the effect of nanoparticles in our case MWCNTs is important.

Different shapes of cavity for HTC have been investigated by Kathiravan et al. [2011]. The test results exhibited that the addition of carbon nanotubes increased boiling heat transfer coefficients of the base fluids. it was found that 0.5% of CNT concentration gives the highest enhancement of 1.7 compared with water.

Experiments were conducted by with bare silicon and fully coated CNT surface at 0°, 30°, 60°, 120°, 150° and 180° by Ho et al.(2014). Results showed that at constant surface orientation of 90°, both the fully coated CNT surface and the interlaced patterned CNT surface enhanced the average heat transfer coefficient by 42%.

Amiri et al. (2014) investigated the effects of carbon nanotubes structures and different functional groups were studied on the pool boiling heat transfer coefficients (HTC) and critical heat fluxes (CHF).

Different orientation of surfaces for HTC have been investigated by Sarafraz & Hormozi [2016] and it has been found nanoparticle deposition causes changes in surface roughness. The experimental heat transfer coefficients were also validated by comparing to the well-known correlations and available data in the literature.

The influences of covalent and non-covalent functionalization on the pool boiling heat transfer performance of MWNTs nanofluids were experimentally investigated by Xing et al. [2016] under different weight concentrations.

Neto et al. [2017] found CHF can be enhanced by complete wettability through using nanoparticles. Boiling curves, critical heat fluxes and heat transfer coefficients were obtained and compared to reference data for water.

The effect of size of the nanoparticles in pool boiling has been investigated by Shoghl et al. [2017]. Their results showed show that the overall effect of ZnO and Al_2O_3 nanoparticles is the deterioration of heat transfer while the addition of CNTs results in improving heat transfer.

Fan et al. [2017] showed by using high concentration of nanofluids surface roughness can be increased. The findings of this work suggested an active approach to optimization of quenching performance of CNT-based nanofluids.

It was observed by Thakur et al. [2021] by using a 0.005 vol% of MWCNT in water, critical heat flux can be enhanced to 2.14 W/m^2. This recorded critical heat flux enhancement is 62.12% more than the critical heat flux required for the water.

Extensive studies have recently been made by using different surfaces, in order to increase rate of heat transfer especially for V shaped groove by Qu et al. [2012] studied the effect of the smooth and rib surfaces under an electric field. They showed that V grooves can enhance the heat transfer coefficient surface at an angle 60°.

Das et al. [2007] showed the channels inclined in pool boiling surface at an angle 60° experimentally with the horizontal give higher rate of heat transfer. Das et al. [2009] reported pool boiling from different smooth surfaces for circular, rectangular shape.

By looking at some published papers related to pool boiling such as, Qu et al. [2012] & Quan et al. [2015] & Sarafraz et al. [2016], it is obvious, grooved surfaces are more commonly preferred choices in the mainstream due to their good thermal performance, but also a low manufacturing cost is considered a merit.

Although a few numbers of grooved surfaces have been introduced for the enhancement of rate of heat transfer in pool boiling, the review of literature made it clear that the mechanism of boiling in groove surfaces with nanofluid especially MWCNTs has not been investigated. In other words, there is no study that has qualitatively described the use of MWCNTs and the boiling behavior detailing the characterizations of smooth and groove surfaces.

Few studies showed a clear and systematic investigation of thermal performance on pool boiling with nanofluids, and it is no unified and quantitative conclusion about the effects of MCWNTs in groove and smooth surfaces. CNT are the promising materials due to their desired thermal properties such as high thermal conductivity compares to Al_2O_3, TiO_2 and CuO, so the purpose of this investigation is to introduce a novel type of grooved surface under pool boiling whilst using MWCNTs. In this study, a novel circular grooved type of boiling heat transfer surface has been designed, constructed and tested. This paper investigates the thermal performances of six distinct surfaces with different concentrations of MWCNTs.

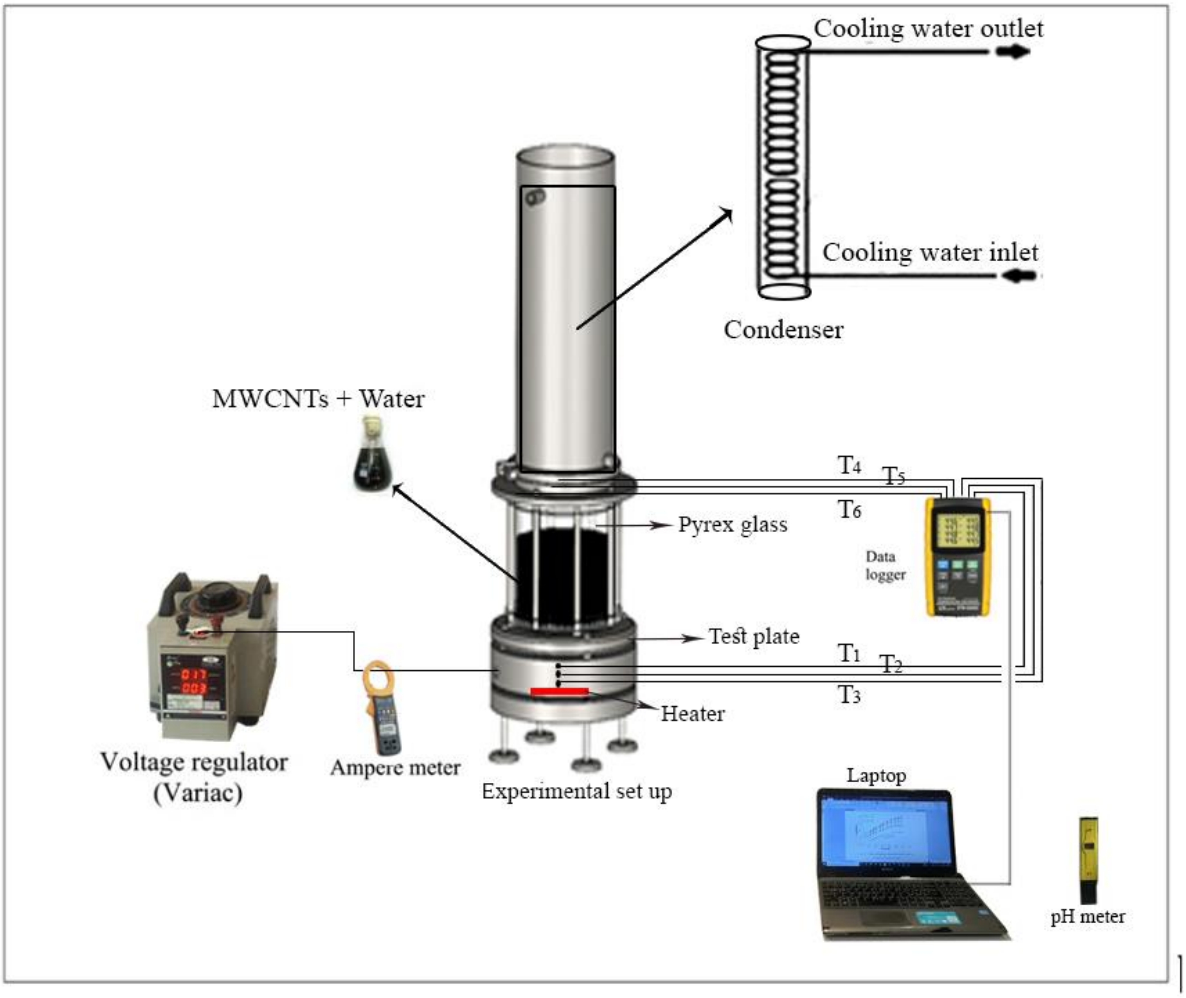
2. Experimental Apparatus

For this research, an experimental setup consisting of a cylindrical boiling vessel shown in Figure 1 has been used. In this paper, a coil heater of 1100W with a diameter of 15 mm and length of 90 mm for initial heating was used during the experiments to provide constant heat flux. Insulation of the bottom side of the heater by Teflon was achieved to make sure we do not have heat loss from the bottom of the vessel.

The condenser with diameter of 90mm and height of 320mm was used for cooling of any vapour which exit also the cooled water with inlet temperature of 18 °C and outlet temperature of 27°C was circulated through tube with a stainless steel (316) diameter of 3mm and length of 200mm. Steady state condition was supposed to be reached, when the recorded temperature difference of each thermocouple became less than 0.5 K/hour. Experiments were conducted in this chamber using distilled water under atmospheric pressure.

The experimental apparatuses are condenser, Pyrex glass, boiling liquid, test plate, heater, Variac, as shown in Figure 1. The boiling vessel with 100 mm diameter Pyrex glass with height of 190 mm, used for this experiment. Aluminium sheets with thermal conductivity of 140 W/m. K has been used in this experimental. The sides of the cylinder are covered with a Teflon insulation. The Teflon material is Polytetra fluoroethylene. A 12 channels K-type thermocouple with a sheath length of 200 mm and a diameter of 5 mm was used. One thermocouple was placed at the bottom of the vessel also one time thermocouples T_2, T_3 and one time thermocouples T_2, T_1 are connected to the surface directly and because we have heat flux (q'') so the surface temperature(T_s) could be measured with more accuracy also three thermocouples were used to measure the liquid to measure the average boiling liquid temperature in different places.

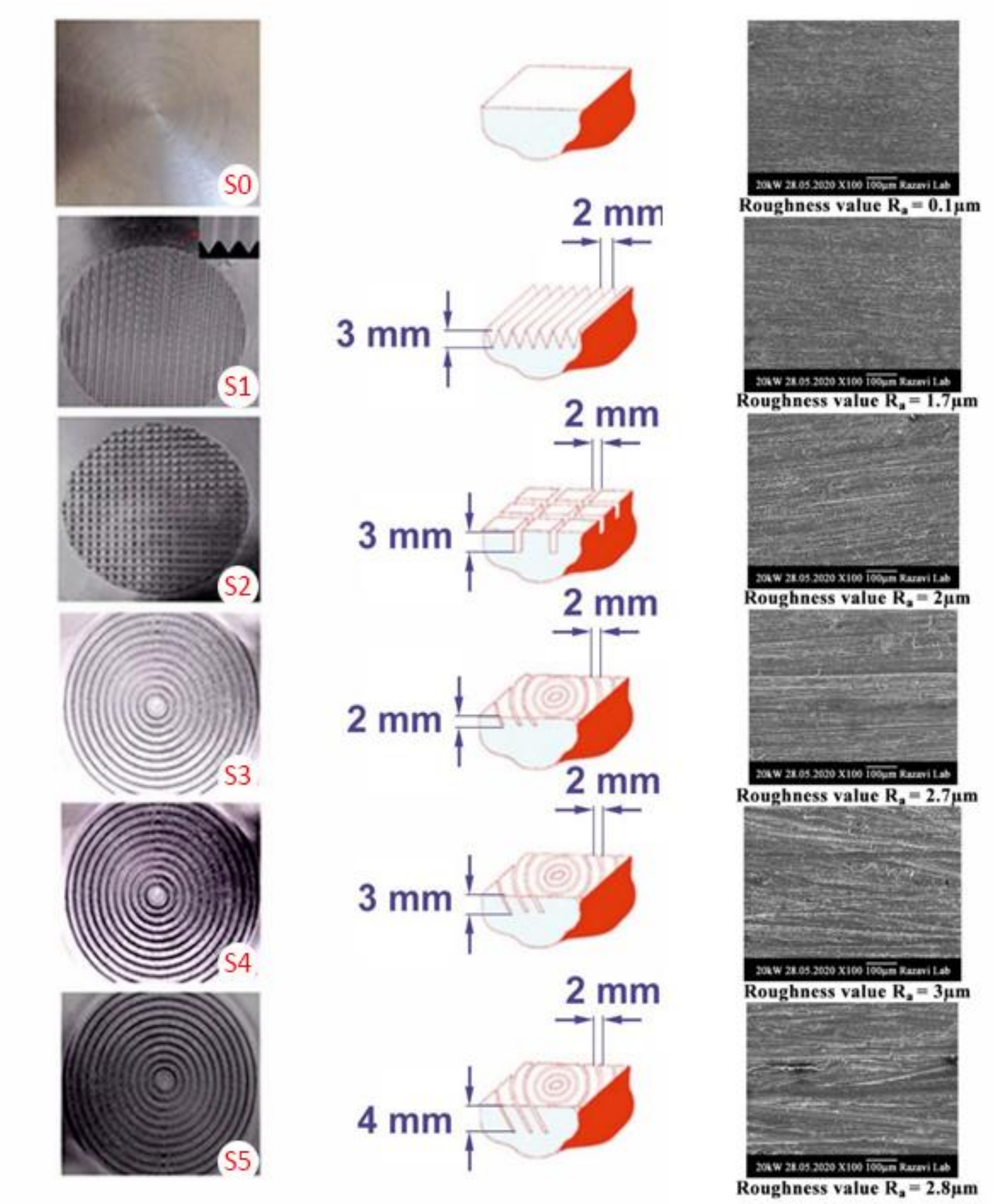
(a)



(b)

Figure. 1 Our experimental set-up: (a) experimental apparatus of test system (b) schematic of test system.

The surface conditions are important factors in pool boiling. As a result, five different shapes of groove have been made examine their efficiency in pool boiling with and without nanofluids. Characterization of shape and geometry for smooth (S0) and grooved surfaces (S1, S2, S3, S4, S5) showed in Table 1. Figure 2a shows various surfaces including smooth (S0) and grooved surfaces (S1, S2, S3, S4, S5), Figure 2b schematic of smooth (S0) and grooved surfaces (S1, S2, S3, S4, S5) Figure 2c shows roughness values for smooth (S0) and grooved surfaces (S1, S2, S3, S4, S5).



(a) **(b)** **(C)**

Figure 2. (a) Various surfaces including smooth (S0) and grooved surfaces (S1, S2, S3, S4, S5),

(b) Schematic of smooth (S0) and grooved surfaces (S1, S2, S3, S4, S5).
(c) Roughness values for smooth (S0) and grooved surfaces (S1, S2, S3, S4, S5).

Table 1. Characterization of geometry for smooth (S0) and grooved surfaces (S1, S2, S3, S4, S5).

No:	Surface area(mm^2)	Depth (mm)	Width (mm)	Inclination (°)
S0	49	-	-	-
S1	75	3	2	45
S2	85	3	2	0
S3	90	2	2	45
S4	94	3	2	45
S5	98	4	2	45

3. Preparation of the nanofluids

For preparing the nanofluids, MWCNTs nanoparticles purchased from Merck Company with a specific density of 2.1 g/cm^3 and thermal conductivity of 3000 W/m K. Specification of Multiwall Carbon Nanotubes (MWCNTs) can be seen in Table 2.

Table 2: Specification of Multiwall Carbon Nanotubes (MWCNTs).

Details	MWCNTs
Purity	95 % wt (carbon nanotubes) 97 % wt (carbon content)
Average diameter	7 nm
Length	10-30 um (TEM)
SSA	110 m^2/g (BET)
Color	Black
Ash	1.5%wt (TGA)
Electrical conductivity	100 s/cm
Specific surface area	60m^2/g

For this study, nanofluid samples were prepared with three MWCNTs concentrations 0.1%, 0.15% and 0.2% by weight and the samples were sonicated in water for 90 minutes. According to Sarafraz et al. [2016] sonication and the suitable pH level and using of Gum Arabic can efficiently crack the agglomeration. Gum Arabic (GA) utilized with a concentration of 0.1% wt to increase the dispersivity. The use of surfactants in our case can reduce the surface tension so with the easier separation of bubbles from the boiling surface, heat transfer coefficient can be increased.

To achieve uniform dispersion and deagglomeration of the MWCNTs particles in the base fluid, ultrasonic the 22 kHz ultrasonic device was used for 90 minutes. The preparation steps are described in Figure 3.

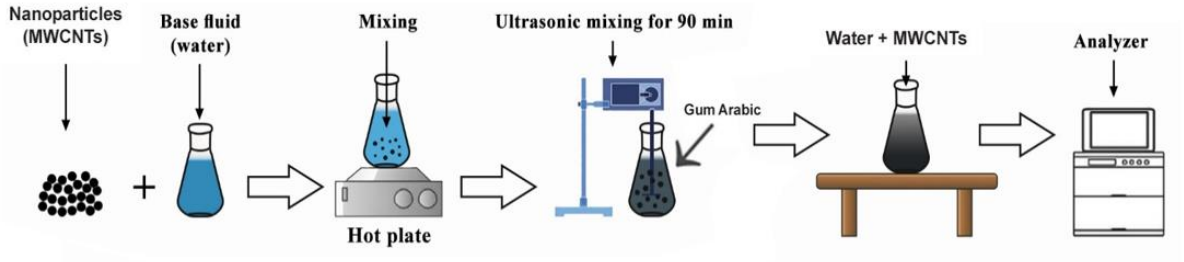


Figure 3. Preparation steps of Multiwall Carbon Nanotube (MWCNT) + water.

For the best stability, pH of nanofluid was set using buffer solution NaOH and HCL (0.1 millimolar). Table 3 shows the stability process for MWCNTs. Our results show pH=8.9 is the most stable for our Nanofluids.

Table 3: The stability process for MWCNTs.

Nanofluid	wt%	Stirring(min)	Sonication(min)	pH setting	Stability
MWCNTs	0.10	90	90	8.2	about 8 hours
	0.15	110	110	8.5	about 12 hours
	0.20	130	130	8.9	about 15 hours

This also insured the stable suspension of the nanoparticles in base fluids without sedimentation. To prepare MWCNTs/water, after magnetic stirring for 90 minutes, then the nanofluid were exposed to an ultrasonic processor with power of 600W. As it can be seen it leads us to a stable suspension with different concentrations. Also Figure 4 shows size distribution by volume and it illustrates the size of our multi wall nano carbon tube is around 7 nm.

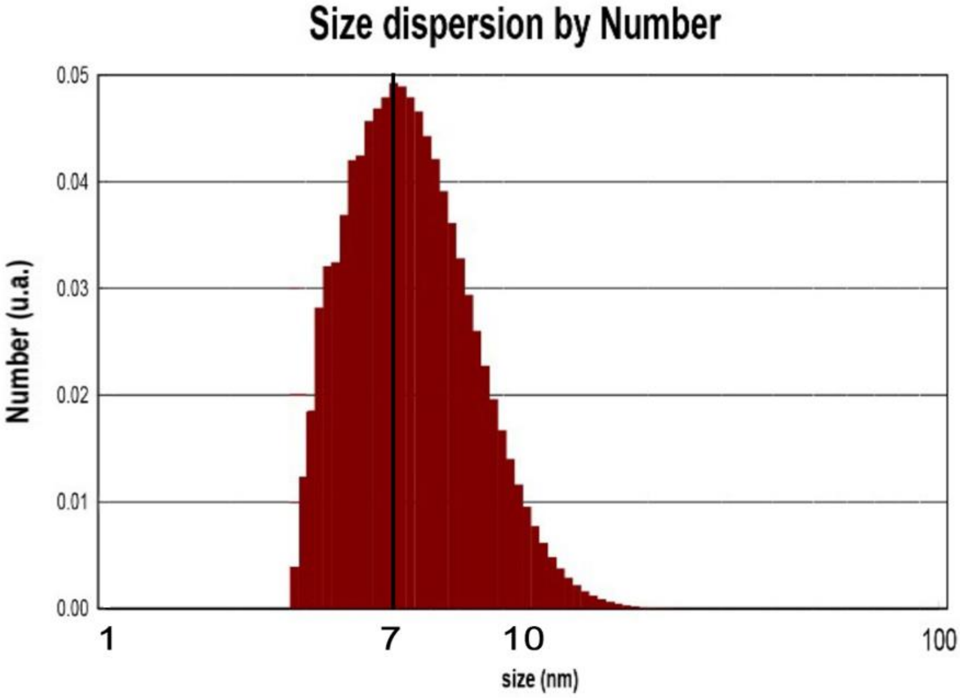


Figure 4. Diameter distribution of the Multiwall Carbon Nanotube (MWCNTs).

The system was stopped after each run for three hours to assume the reproducibility and repeatability of the recoding. To ensure the results were correct, each experiment was repeated 3 times with the same procedure and exact amount of MWCNTs + water nanofluid and all of the conditions were kept almost identical during each experiment.

The exceptional repeatability can be attributed to the fact that nanoparticles' random motion under the effect of buoyancy in the base liquid could create uniform nanofluid. The test results can be well repeated for a uniformly dispersed nanofluid.

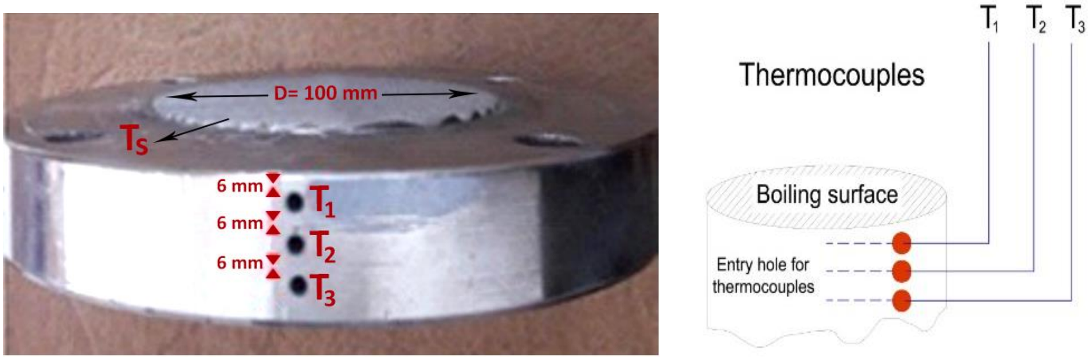
The main disadvantage of nanoparticles are that they are unstable. Preparation of stable nanofluid is critical to measure the thermophysical. The exceptional repeatability can be attributed to the fact that experimental equipment is a more stable and having good working environment.

3.1. Data processing

First we can calculate the heat flux by below equation:

$$q'' = \frac{IV}{A} \tag{1}$$

In this equation I stands for the current (Amps), V shows the voltage (Volts), A also refers to the heating surface area (m^2) which can be calculated from $A = \pi DL$ and D is the diameter of the heater vessel so the value of q" can be found. Because the heat conducted inside the heater is in one dimension and the heat flux can be obtained from the tested temperatures T_1, T_2, and T_3 which is shown in Figure 5. Thermocouples T_1, T_2 and T_3 are connected to the surface directly so the surface temperature(T_s) measured with more accuracy. The authors used this method in order to reduce the effect of heat loss on heat transfer performance.



(a) (b)

Figure 5. (a) Experimental setup of the surface (b) Boiling surface with three thermocouples embedded inside it.

One-dimensional heat conduction for heater can be express as:

$$q'' = k\frac{dT}{dx}\,|_s \tag{2}$$

In this equation k is the aluminum thermal conductivity where k=140 W/m. K and x= 12mm.

$$q'' = k\ \frac{\partial T}{\partial x} = k\ \frac{(T_3 - T_2)}{x} \tag{3}$$

Also we have:

$$q'' = k\ \frac{\partial T}{\partial x} = k\ \frac{(T_2 - T_1)}{x} \tag{4}$$

We can find out the heat Flux for Equation 3 and 4 are the same, as the results we have:

$$q'' = k\ \frac{\partial T}{\partial x} = k\ \frac{(T_3 - T_1)}{2x} \tag{5}$$

And now by using “Eq. (5)” we can calculate the mean surface temperature (T_s).

$$T_s = T_1 - q''(\frac{x}{k}) \tag{6}$$

And finally we are able to find the heat transfer coefficient from “Eq. (7)”

$$h = \frac{q''}{T_s - T_{sat}} \tag{7}$$

All the properties of MWCNTs/water nanofluids were applied with the average temperature of the MWCNTs/water nanofluids and the thermal conductivity (k), viscosity (μ), specific heat (c_p) and density (ρ) were calculated by the following (Hemmat Esfe et al. 2014):

$$\rho = (1 - \varphi)\rho_w + \varphi\rho_p \tag{8}$$

where φ denoted the volume fraction of the MWCNTs/water nanofluids, ρ_w and ρ_p were the bulk densities of water and MWCNTs nanoparticles, respectively . Equation 8 shows that the addition of nanoparticles to the base fluid increase the thermal conductivity fluid flow.

$$c = \frac{(1 - \varphi)\ \rho_w c_w + \varphi\rho_p\ c_p}{\rho} \tag{9}$$

where c_w and c_p were the specific heat of water and MWCNTs nanoparticles, respectively.

$$\mu = \frac{1}{(1 - \varphi)^{2.5}}\ \mu_w\ \frac{\rho_w}{\rho} \tag{10}$$

where μ_w was the viscosity of water

$$k = \frac{k_p + 2k_w + 2(k_p - k_w)\varphi}{k_p + 2k_w - 2(k_p - k_w)\varphi} \tag{11}$$

Where k_w and k_p were the thermal conductivity of water and MWCNTs nanoparticles, respectively.

3.2. Uncertainty analysis

Uncertainty in this paper was mainly due to the measured temperatures by 12 channels. Thermocouples were connected to temperature data logger model BTM-4208SD. In order to validate the reliability of the experimental device and the data analysis, a boiling experiment is carried out using DI water. Uncertainty of the measured parameters has been shown in Table 4.

Table 4: Measured parameters and their uncertainties in this experiment.

Measured quantity	Uncertainty
Distance	0.1 mm
Temperature	±0.1K
Voltage	1 V
Amperage	0.1 A
Roughness	0.05 μm
Thermal conductivity	0.01 W/m. K

Uncertainties in heat transfer coefficient and heat flux were found to be in a range of 2–6%, and 2– 5% respectively for all fluids tested. The relative uncertainty can be calculated as shown below:

$q'' = f(\Delta T, \Delta x)$

$$\frac{U_{q''}}{q''} = (\left(\frac{U_{T_3-T_1}}{T_3-T_1}\right)^2 + \left(\frac{U_{X_3-X_1}}{X_3-X_1}\right)^2)^{0.5} \tag{12}$$

$T_s = f(L, q^{"})$

$$\frac{U_{q''}}{q''} = (\left(\frac{U_{T_1-T_{sat}}}{T_1 - T_{sat}}\right)^2 + \left(\frac{U_L}{L}\right)^2)^{0.5} \tag{13}$$

$h = f(\Delta L, q^{"})$

$$\frac{U_h}{h} = (\left(\frac{U_{q''}}{q''}\right)^2 + \left(\frac{U_{\Delta T_S}}{\Delta T_S}\right)^2)^{0.5} \tag{14}$$

4. Results and Discussion

As demonstrated by Das et al. [2017] & Tian et al. [2019], the effect of surface roughness by grooving on the film boiling cannot be neglected. The aim of this novel study is to compare the boiling heat transfer coefficient of six surfaces through using different concentrations of MWCNTs with various surfaces.

Heat transfer coefficient versus temperature differences in pure water for S0, S1, S2, S3, S4 and S5 which has been shown in Figure 6. Because of using groove surfaces, the heat transfer coefficient is increased. This is expected because the groove surfaces yield more heating surfaces area. However, the interesting point is that the surface S4 have better boiling heat transfer coefficient than surface S5, while heat transfer area of the former is less than the latter. This can be attributed to the position of the heating surfaces.

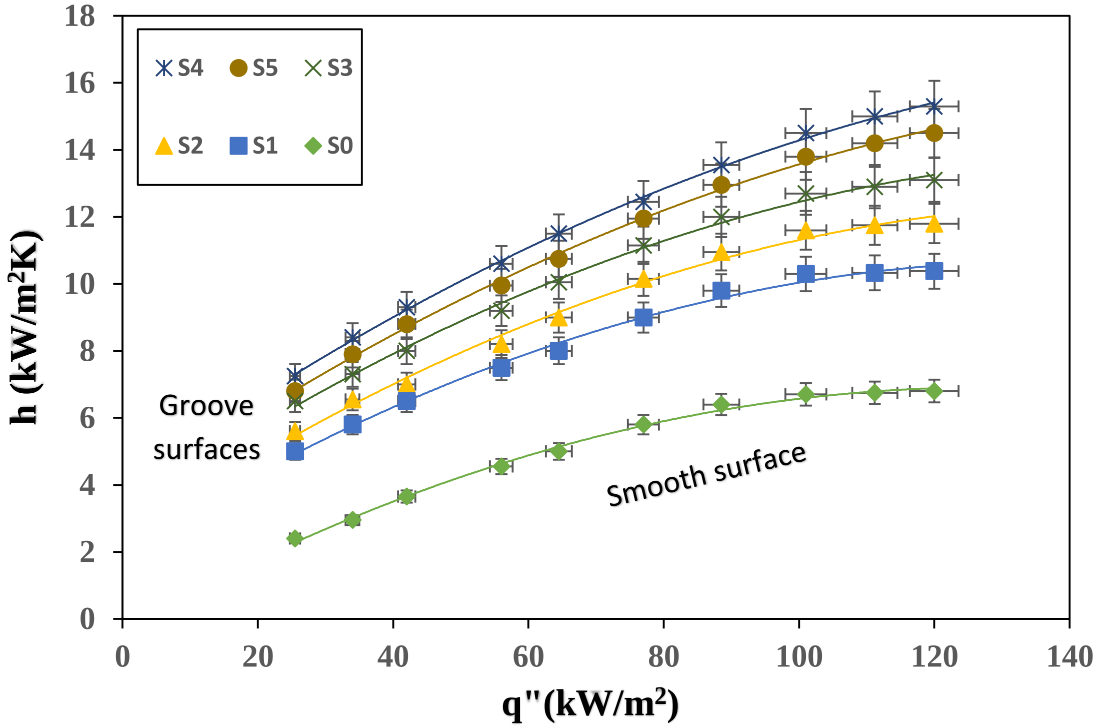


Figure 6. Coefficient of heat transfer of water vs heat flux for S0, S1, S2, S3, S4 and S5.

The use of MWCNTs can reduce the surface temperature and also the wall temperature reduction not only increases with heat flux enhancement as the result of heat transfer coefficient but also goes on a rise with increasing nanoparticles concentration Modi et al. [2020]. Figure 7, shows boiling heat transfer coefficient vs heat flux for MWCNTs with 0. 1% concentration for S0, S1, S2, S3, S4 and S5. It can be found out from Figure 8 increasing the concentration of MWCNTs nanoparticles increases the pool boiling heat transfer coeffient.in the boiling process over all the heating surfaces.

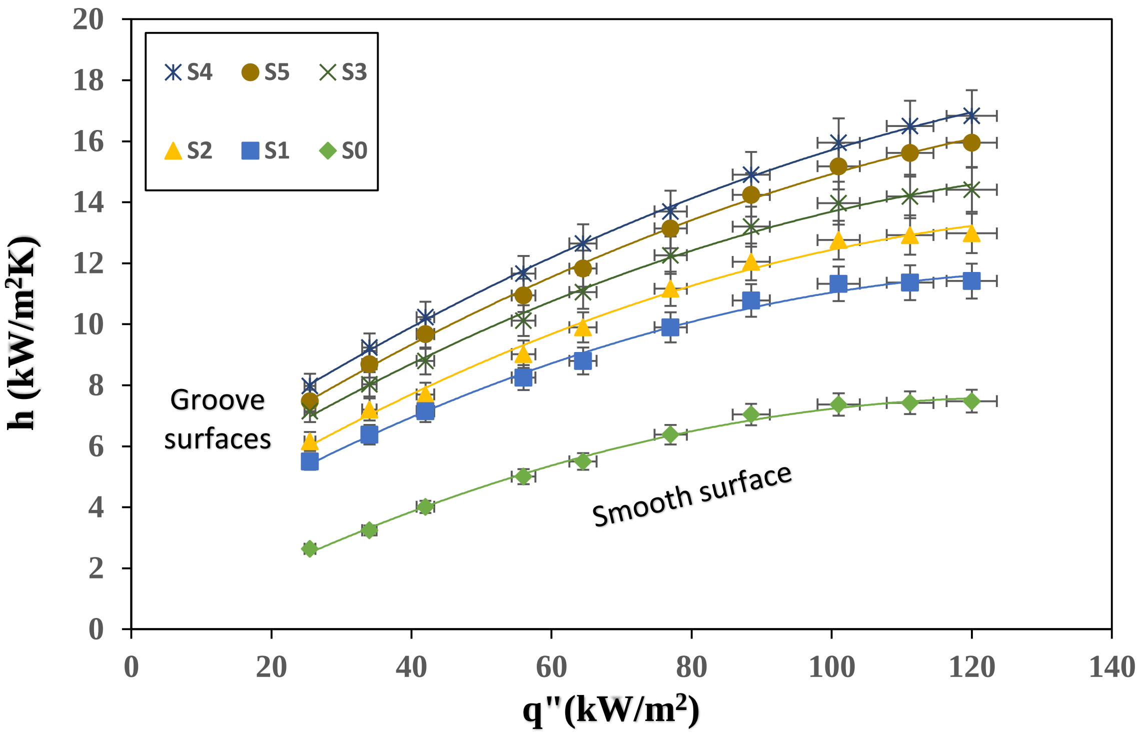


Figure 7. Coefficient of heat transfer vs heat flux for MWCNTs with 0. 1% concentration for S0, S1, S2, S3, S4 and S5.

Figure 8, shows boiling heat flux us temperature differences for MWCNTs with 0.15% concentration for S0, S1, S2, S3, S4 and S5. We can see from the graph groove surfaces with higher concentration of MWCNTs, higher heat transfer coefficient compared with smooth surface.

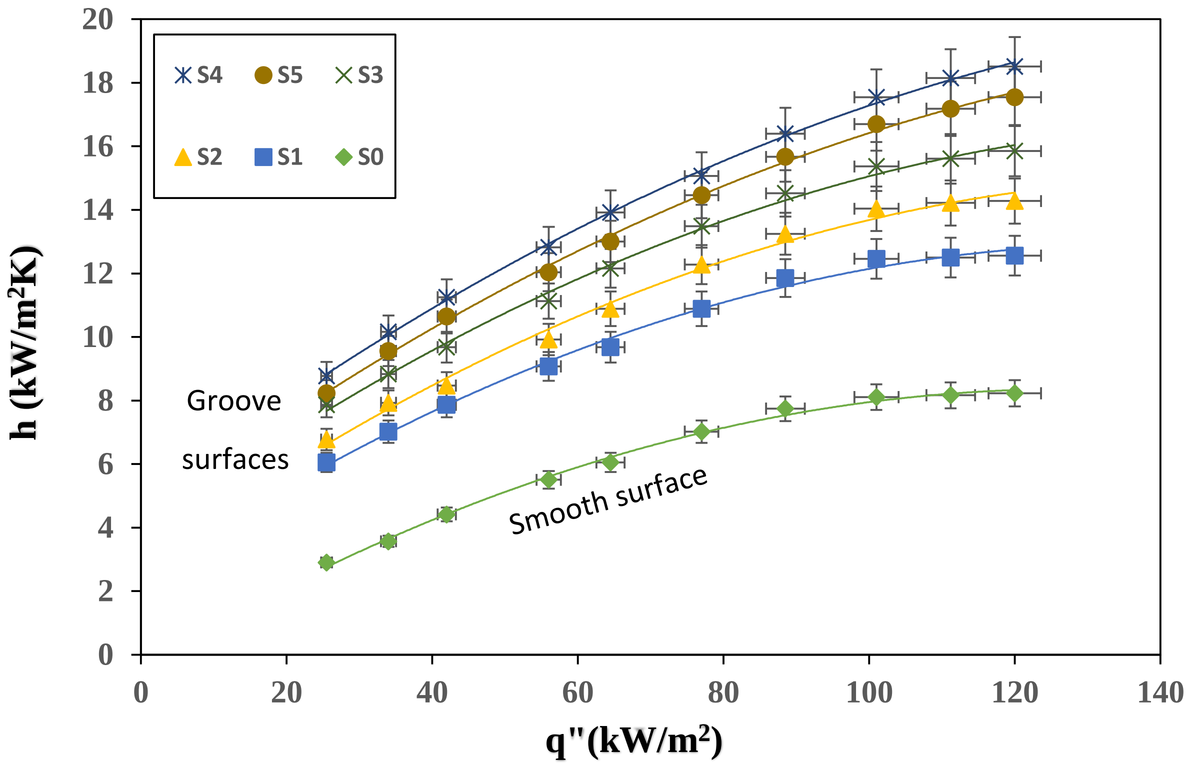


Figure 8. Coefficient of heat transfer vs heat flux for MWCNTs with 0.15% concentrations for S0, S1, S2, S3, S4 and S5.

Figure 9 shows boiling heat transfer coefficient versus heat flux for for MWCNTs with 0.2% concentration for S0, S1, S2, S3, S4 and S5. Higher thermal conductivity of a nanofluid (in our case MWCNTs) has a significant effect on the boiling heat transfer coefficient enhancement. The presence of nanoparticles causes the collision between the heating surface and the particles, thereby causing increased turbulence of the solution and, as a result, higher heat transfer coefficients (Dehghani et al. 2018).

Higher thermal conductivity of a nanofluid (in our case MWCNTs) has a significant effect on the boiling heat transfer coefficient enhancement. The presence of nanoparticles causes the collision between the heating surface and the particles, thereby causing increased turbulence of the solution and, as a result, higher heat transfer coefficients (Dehghani et al. 2018).

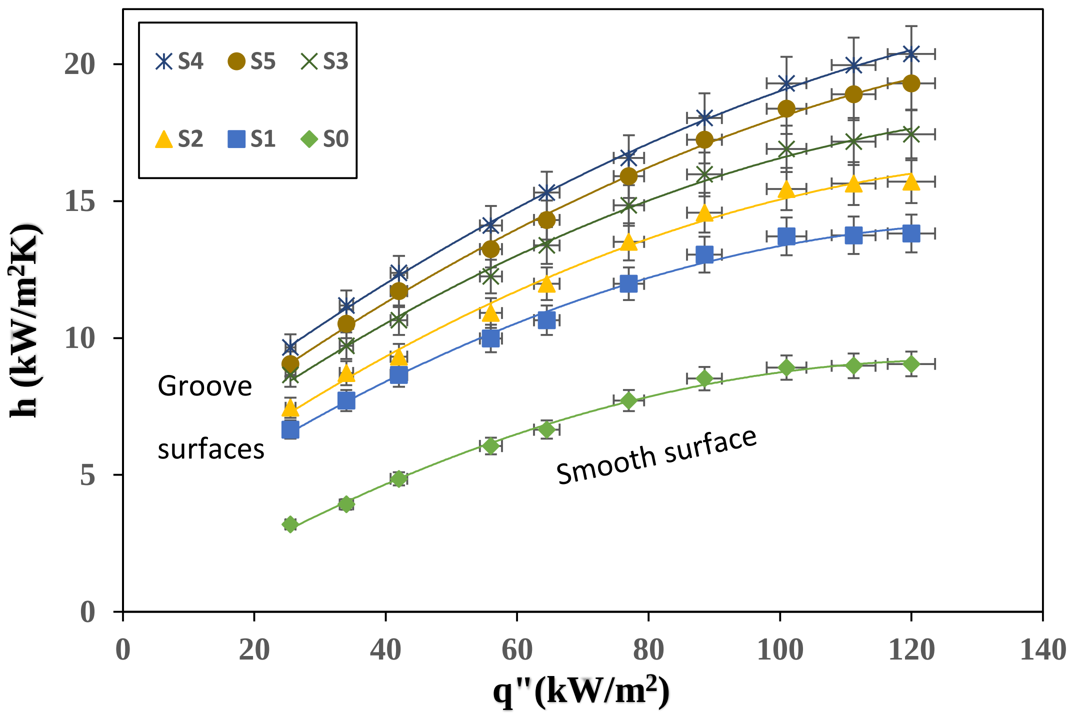


Figure 9. Coefficient of heat transfer vs heat flux for for MWCNTs with 0.2% concentration for S0, S1, S2, S3, S4 and S5.

In order to evaluate nanofluid boiling heat transfer coefficient enhancement compare to water with increasing nanoparticles concentration and heat flux, the heat transfer coefficient ratio of MWCNTs + water nanofluid to water is shown in Figure 10. As it can be seen this ratio is increased with nanoparticles concentration increasing. For example, by increasing nanofluid concentration from 0.1% to 0.2% at q"=110 kW/m^2 this ratio increases from 1.16 to 1.42.

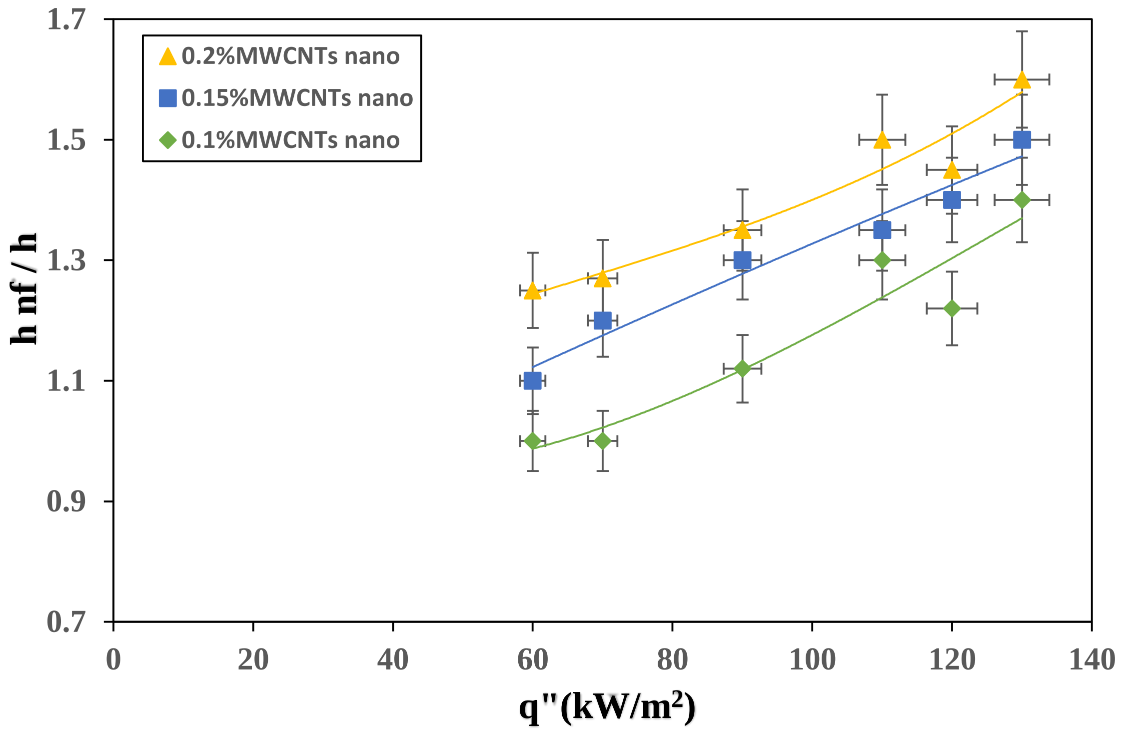


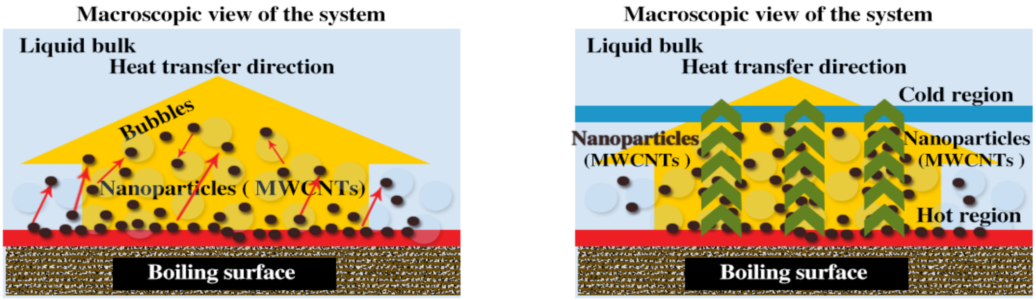
Figure: 10. The ratio of boiling heat transfer coefficient of MWCNTs+ water nanofluid to water vs heat flux at different nanoparticle concentrations.

This enhancement in the heat transfer coefficient (HTC) value is attributed to the micro-mechanisms activated in the bulk of the water due to the presence of the Multiwall Carbon Nanotubes (MWCNTs)/water nanofluid, which are discussed below:

(a) Brownian motion: The first micro-mechanism is referred to as "Brownian motion", is sourced from the random movement and collision of the nanoparticles within the bulk of the liquid. Such short random movements (length of movement is potentially equivalent to the mean free path of two particles) increase the probability of the collisions between particles and between the particles and micro-layers of the base fluid, which in turn facilitates the conduction heat transfer (due to the collision of the particles) and convective heat transfer (during migration between the layers of the base fluid). Notably, such movements can also induce micro-streams of convection, which locally increases the heat transfer coefficient. Such

movements can create distortion in the thermal boundary layer resulting in the increase in HTC value of the system.

(b) Thermophoresis effect: The second contributor is the “thermophoresis phenomena” which is sourced from the temperature difference between two different regions of the bulk of the NS. Such temperature gradient can stimulate the nanoparticle to mi- grate from a hot region towards the cold one. In the hot region, due to the conduction and/or convective mechanism, thermal energy is absorbed by the nanoparticles, which is then delivered to the cold region with the same mechanisms. Thus, these two contributors can facilitate the heat transfer and augment the HTC value. A schematic illustration of the mechanisms improving the thermal performance of the system is shown in Figure 11 (Li et al. 2020 & Yao et al. 2019).



(a) **(b)**

Figure 11. a) Brownian motion b) Thermophoresis.

Figure 12 illustrates that a groove surface has many cavities that can be used to trap vapour, providing more and large sites for bubble growth. By comparing Fig. 6 and Fig. 9, the experimental results revealed with 0.2% MWCNTs-water by weight gave the best enhancement of heat transfer coefficient approximately by 33%.

By using grooved surface especially inclined circular groove at angle of 45° (S4) with roughness value of R_a= 3µm it creates more bubbles and providing more nucleation sites as a result, higher heat transfer coefficients (see Figure 12). Comparing the surface S3 with roughness value of R_a= 2.7µm and S4 with roughness value of R_a= 3µm and no trapped vapor and S5 with roughness value of R_a= 2.8µm with tunnel with trapped vapor and also due to the porous deposition layer formed by the deposition of the nanoparticles, which increases the thermal resistance of the heat conduction shows surface S4 is the best boiling surface.

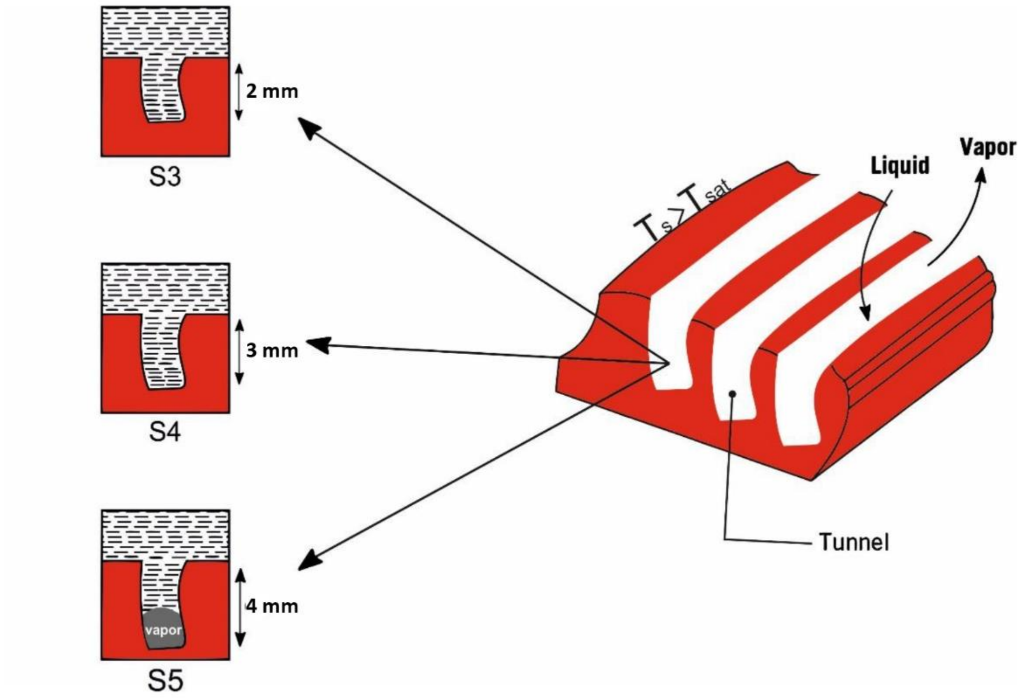


Figure 12. Schematic of hypothesis for water film structure in pool boiling for grooved surfaces S3, S4 and S5.

To find out the augmentation factor for all the surfaces below equation can be used (Das et al., 2009):

$$\left(\sum_{for\ all\ n} \frac{q|\Delta T, structured\ surface}{q|\Delta T, plane\ surface} \right) / \, n \qquad (15)$$

From Table 5 and Figure 11 it can be found out the surface area of S5 is higher compared to S4 but augmentation factor of the S5 is lower compared to surface of S4. This indicates that for enhancement of coefficient of heat transfer release of generated bubble is very important parameter.

Table 5. Enhancement factors for different geometry.

No:	$\frac{\pi D^2/4 + Cavity\ area}{\pi D^2/4}$	Augmentation factor
S0	1	0
S1	2.41	5.8
S2	2.64	6.45
S3	2.54	6.85
S4	3.10	8.30
S5	3.25	7.20

5. Conclusions

Review of literature revealed lack of work around the mechanism of boiling on groove surfaces with nanofluid especially MWCNTs. This paper showed the heat transfer coefficient comparison between grooved surfaces and smooth surface under pool boiling in presence of Multi Wall Carbon Nanotube (MWCNTs) nanoparticles at different concentrations (0.1%, 0.15% and 0.2%) within the base fluid. Based on pool boiling surfaces, a new type of groove pool boiling surface was designed and constructed, which is consisted of inclined circular groove. The experimental results exhibited that boiling heat transfer coefficient was about 33% higher for 0.2% concentration of MWCNTs. The experimental results for six surfaces arrangement in pool boiling revealed that:

(a) By using grooved surface especially inclined circular groove at angle of 45° (in our case S4) and using MWCNTs the contact between nanofluid particles and the surface increase, create more bubbles so higher heat transfer coefficients can be achieved.

(b) Grooved surfaces enhanced the heat transfer coefficient (h) and it was obtained in circular grooves, which is 33% higher than the base fluid water on the smooth surface. This shows the release of generated bubble is also important along with the additional surface for bubble generation for enhancement of boiling heat transfer. This is an important observation and to the best of the knowledge of the authors this has not been reported earlier.

(c) For grooved surfaces, the highest increase in heat transfer coefficient (h) was seen in circular grooves (S4) with higher roughness value compare to S5 with depth of 30mm consisting of circular groove inclined at angle of 45°.

(d) Comparing surface S3 of short wetted channel and S4 of wetted tunnel with no trapped vapor and S5 of reentrant tunnel with trapped vapor and also due to the porous deposition layer formed by the deposition of the nanoparticles, which increases the thermal resistance of the heat conduction shows surface S4 is the best boiling surface. For case of surface S5 sedimentation of nanoparticles cannot form more nucleation sites as well as acts an insulation layer on the surface. Here, in addition of thermal resistance of nanolayer, an extra resistance due to blocked vapor in the cavities, results in more deterioration of heat transfer coefficient.

(e) The enhanced heat transfer of grooved surfaces is not merely related to the increased heat transfer area, but also the situation of the grooved has a prominent role in the boiling characteristics.

Ethical Approval: Not applicable

Consent to Participate: Not applicable

Consent to Publish: Not applicable

Authors Contributions:

A. Vasei Moghadam: Experiments, drafted the manuscript text and provide the figures and tables. **H. R. Goshayeshi:** All experiments are done under his supervision and manuscript text, figures and tables are rewritten based on his comments. **I. Chaer:** Checking all manuscript and commented for improving it. **A. Paurine:** Checking all manuscript and commented for improving it. **S. Zeinali Heris:** Checking all manuscript and commented for improving it and also proposing to add some new experimental results to manuscript.

Funding: The present research received no funding.

Competing Interests: The authors declare that they have no competing interests

Availability of data and materials: All data generated or analyzed during this study are included in this published article

References

Ahmad F, Ahmad Khan W (2021) Energy enhancement of an air-conditioner utilizing nanofluid: An experimental study. Energy Reports. 7:575-583. https://doi.org/10.1016/j.egyr.2021.01.023.

Ali HM., Generous MM., Ahmad F, Irfan M (2017) Experimental investigation of nucleate pool boiling heat transfer enhancement of TiO_2-water based nanofluids, Applied Thermal Engineering. 113:1146-1151. https://doi.org/10.1016/j.applthermaleng.2016.11.127.

Amiri A, Shanbedi M, Amiri H, Heris SZ, Kazi S. N, Chew BT, Eshghi H (2014) Pool boiling heat transfer of CNT/water nanofluids. Applied Thermal Engineering. l: 450-459. https://doi.org/10.1016/j.applthermaleng.2014.06.064

Arenales M, Kumar S, Kuo L, Chen P (2020) Surface roughness variation effects on copper tubes in pool boiling of water, Int J Heat Mass Transf. 151:119399. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119399.

Cao Y, Thanh Nguyen P, Jermsittiparsert K, Belmabrouk H, Alharbi SO, Khorasani MS (2020) Thermal characteristics of air-water two-phase flow in a vertical annularly corrugated tube. Journal of Energy Storage. 31: 101605. https://doi.org/10.1016/j.est.2020.101605.

Dai X., Huang X, Yang F, Li X, Sightler JY, Yang J., Li, C (2013) Enhanced nucleate boiling on horizontal hydrophobic-hydrophilic carbon nanotube coatings. Appl. Phys. Lett. 102: 161605. doi: 10.1063/1.4802804. https://doi.org/10.1063/1.4802804.

Dadjoo M, Etesami N, Esfahany M. N (2017) Influence of orientation and roughness of heater surface on critical heat flux and pool boiling heat transfer coefficient of nanofluid, J Applied Thermal Eng. 124: 353-361. https://doi.org/10.1016/j.applthermaleng.2017.06.025.

Das AK, Das PK, Saha P (2007) Nucleate boiling of water from plain and structured surfaces. Experimental Thermal and Fluid Science. 31: 967-977. https://doi.org/10.1016/j.expthermflusci.2006.10.006.

Das AK, Das PK, Saha, P (2009) Performance of different structured surfaces in nucleate pool boiling. Applied Thermal Engineering. 29: 3643-3653. https://doi.org/10.1016/j.expthermflusci.2006.10.006.

Das S, Saha B, Bhaumik S (2017) Experimental study of nucleate pool boiling heat transfer of water by surface functionalization with crystalline TiO_2 nanostructure, Applied Thermal Engineering. 113: 1345-1357. https://doi.org/ 10.1016/j.applthermaleng.2016.11.135.

Dehghani E,.Salimpour M R (2018) Effect of groove geometry on pool boiling heat Transfer of water-titanium oxide nanofluid, Int. J. Heat Mass Transfer. 11: 3473-3481. https://doi.org/ 10.1007/s00231-018-2388-1.

El-Khouly MM, El Bouz MA., Sultan G.I, (2021) Experimental and computational study of using nanofluid for thermal management of electronic chips, Journal of Energy Storage. 39: 102630. https://doi.org/10.1016/j.est.2021.102630.

Fan L, Li J. Q, Wu YZ, Zhang L, Yu Z T (2017) Pool boiling heat transfer during quenching in carbon nanotube (CNT)-based aqueous nanofluids: Effects of length and diameter of the CNTs, Applied Thermal Engineering. 122: 555-565. https://doi.org/10.1016/j.applthermaleng.2017.05.036.

Guo D, Li X. Zhang H, Li F, Su W (2020) Bubble behaviors during subcooled pool boiling in water and nonionic surfactant aqueous solution, Int. J. Heat Mass Transf. 159: 12087. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120087

.Ham J, Kim H, Shin Y, Cho H (2014) Experimental investigation of pool boiling characteristics in Al_2O_3 nanofluid according to surface roughness and concentration, J Thermal Sciences. 114: 86-97. https://doi.org/10.1016/j.ijthermalsci.2016.12.009.

Hemmat Esfe M, Saedodin S, Mahian O, Wongwise S. (2014) Thermophysical properties, heat transfer and pressure drop of COOH-functionalized multi wall carbon nanotubes/water nanofluids. International Communications in Heat and Mass Transfer. 58: 176-183. https://doi.org/10.1016/j.icheatmasstransfer.2014.08.037.

Ho JY, Leong KC, Yang C (2014) Saturated pool boiling from carbon nanotube coated surfaces at different orientations. Int J Heat Mass Transfer. 79: 893-904. https://doi.org/10.1016/j.ijheatmasstransfer.2014.08.053.

Karimipour A (2015) New correlation for Nusselt number of nanofluid with Ag/Al_2O_3/Cu nanoparticles in a microchannel considering slip velocity and temperature jump by using lattice Boltzmann method, J. Thermal Science. 91: 146-156. https://doi.org/10.1016/j.ijthermalsci.2015.01.015.

Kathiravan R, Kumar R., Gupta A, Chandra R, Jain PK (2011) Pool boiling characteristics of Multiwall Carbon Nanotube (CNT) based nanofluids over a flat plate heater, Int. J. Heat Mass Transfer. 54: 1289-1296. https://doi.org/10.1016/j.ijheatmasstransfer.2010.10.002.

Kwark SM, Kumar R, Moreno G, Yoo J, Yoo SM (2010) Pool boiling characteristics of low concentration nanofluids, J Heat and Mass Transfer 53: 972-981. https://doi.org/10.1016/j.ijheatmasstransfer.2009.11.018.

Li Z, Mazinani A, Yayat T, Al-Rashed A, Alsulami H, Goodarzi M, Sarafraz M. (2020) Transient pool boiling and particulate deposition of copper oxide nano-suspensions. International Journal of Heat and Mass Transfer. 155: 119743. http:///doi/10.1016/j.ijheatmassstransfer.2020.119743.

Mahmoudi M., Tavakoli M. R, Mirsoleimani MA, Gholami A, Salimpour MR (2017) Experimental and numerical investigation on forced convection heat transfer and pressure drop in helically coiled pipes using TiO_2/water nanofluid, Int. J. Refrig. 74: 625-641. https://doi.org/10.1016/j.ijrefrig.2016.11.014.

Mehralizadeh A, Shabanian S R, Bakeri G (2019) Effect of modified surfaces on bubble dynamics and pool boiling heat transfer enhancement: A review, Thermal Science and Engineering progress, https://dio.org/10.1016/g.tsep.2019.100451.

Mirziei M (2017) Experimental investigation of the assessment of Al_2O_3-H_2O, and CuO-H_2O nanofluids in a solar water heating system, Journal of Energy Storage. 4: 71-81. https://doi.org/10.1016/j.est.2017.09.012.

Modi M, Kangude P, Srivastava A (2020) Performance evaluation of alumina nanofluid and nanoparticles deposited surface on nucleate pool boiling phenomena. Int. J. of Heat and Mass Transfer. 146: 118-133. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118833.

Neto A R., Oliveira J. L. G., Passos J C (2017) Heat transfer coefficient and critical heat flux during nucleate pool boiling of water in the presence of nanoparticles of alumina, magnetite and CNTs. Applied Thermal Engineering. 111: 1493-1506. https://doi.org/10.1016/j.applthermaleng.2016.06.130.

Qu ZG., Xu Z, Zhao C, Tao W (2012) Experimental study of pool boiling heat transfer on horizontal metallic foam surface with crossing and single- directional V- shaped grooved in saturated water, Int. J. of multiphase flow. 41: 44-55. https://doi.org/10.1016/j.ijmultiphaseflow.2011.12.007.

Quan X, Gao M, Cheng P, Li J (2015) An Experimental investigation of pool boiling on smooth/rib surfaces under an electric field. Int. J. Heat Mass Transfer. 85: 595-606. https://doi.org/10.1016/j.ijheatmasstransfer.2015.01.083.

Salimpour M R, Golmohammadi K, Sedaghat A (2015) Campo A, Experimental study of turbulent convective heat transfer of titanium oxide nanofluid flowing inside helically corrugated tubes, J. Mech. Sci. Technol. 29: 4011-4016. https://doi.org/ 10.1007/s12206-015-0847-x.

Sarafraz MM, Hormozi F, Silakhori M, Peyghambarzadeh S. M (2016) On the fouling formation of functionalized and non-functionalized carbon nanotube nano-fluids under pool boiling condition. Applied Thermal Engineering. 95: 433–444. https://doi.org/10.1016/j.applthermaleng.2015.11.071.

Sarafraz MM., Hormozi F (2016) Comparatively experimental study on the boiling thermal performance of metal oxide and multi-walled carbon nanotube nanofluids, Powder Technology. 287: 412-430. https://doi.org/10.1016/j.powtec.2015.10.022.

Sarafraz MM, Pourmehran O, Yang B, Arjomandi M, Ellahi R. (2020) Pool boiling heat transfer characteristic of iron oxide nano-suspension under constant magnetic field.

International Journal of Thermal Sciences. 147: 106131. https://doi.org/10.1016/j.ijthermalsci.2019.106131.

Shahmorad Z, Etesami N, Nasr Esfahani M (2013) Pool boiling characteristics of nanofluid on flat plate based on heater surface analysis. International Communication in Heat and Mass Transfer. 47: 113-120. https://doi.org/10.1016/j.icheatmasstransfer.2013.06.006.

Shoghl S N, Bahrami M, Jamialahmadi M (2017) The boiling performance of ZnO-Al_2O_3 and MWCNTs/water nanofluids: An experimental study. Experimental Thermal and Fluid Science. 80: 27-39. https://doi.org/10.1016/j.expthermflusci.2016.07.024.

Thakur Thakur P, Kumar N, Sonawane Sh (2021) Enhancement of pool boiling performance using MWCNT based nanofluids: A sustainable method for the wastewater and incinerator heat recovery, Sustainable Energy Technologies and Assessments. 45: 101115. https://doi.org/10.1016/j.seta.2021.101115.

Tian Z, Etedali S, Afrand M, Goodarzi M (2019) Experimental study of the effect of various surfactants on surface sediment and pool boiling heat transfer coefficient of silica/DI water nano-fluid. Powder Technology.336: 391-402. https://doi.org/10.1016/j.powtec.2019.08.049.

Yao Sh, Teng Z (2019) Effect of Nanofluids on Boiling Heat Transfer Performance. Journal of Applied Science 9: 2818. http://doi:10.3390/app9142818.

Xing MB, Yu J. L, Wang R. X (2016) Effects of surface modification on the pool boiling heat transfer of MWNTs/water nanofluids. Int. J. Heat Mass Transfer. 103: 914-919. https://doi.org/10.1016/j.ijheatmasstransfer.2016.07.053.

Xia G, Du M, Cheng L, Wang W (2017) Experimental study on the nucleate boiling heat transfer characteristics of a water-based multi-walled carbon nanotubes nanofluid in a confined space, Int. J. Heat Mass Transf. 113: 59-69. https://doi.org/10.1016/S0894-1777(03)00076-1.

Xu Z, Qin J, Ma X (2021) Experimental and numerical investigation on bubble behaviors and pool boiling heat transfer of semi- modified copper square pillar arrays. International Journal of Thermal Sciences.160106680. https://doi.org/10.1016/j.ijthermalsci.2020.106680.