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RESEARCH ARTICLE

Boiling Thermal Performance of TiO_2 Aqueous NanoFluids as a Coolant on a Disc Copper Block

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Abstract

This work focuses on potential application of nano-fluids in cooling of high heat flux surfaces. For this purpose, experimental studies have been performed to quantify the heat transfer coefficient of Titana (TiO_2) aqueous nano-fluids under different operating conditions. Boiling mechanism is established on a disc copper made heater at different heat flux, mass concentration of nano-fluids and sub-cooling temperatures. Results demonstrated that heat transfer coefficient of Titana nano-fluids are relatively higher than that of the base fluid. Heat and mass concentration of nano-particles can intensify the pool boiling heat transfer coefficient, while sub-cooling temperature can only have impacts on bubble formation. Also, visual study demonstrates that fouling formation of nano-particles can intensify the bubble transport due to the intensification of nucleation sites in the boiling surface.

Keywords

Pool Boiling, TiO_2, Bubble formation, fouling, heat flux, nanofluid

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1 Introduction

Critical Heat Flux, (CHF) in boiling heat transfer, as a definition, is the limited point in which, phase change process acts in a way that bubbles can fully cover and overwhelm the heating surface and lead to the overheating problem. In this condition, heat transfer coefficient starts to be deteriorated over the higher given heat fluxes, which can finally damage to the surface or explode the heater, since heat cannot be transferred from the surface towards the bulk of coolant. Therefore, in order to have efficient cooling system, CHF should be prevented.

Nano-fluids are engineered colloid which are comprised of solid particles 0-100 nm dispersed into the conventional coolant e.g. water, ethylene glycol and are nominated as a promising way to enhance the thermal performance of cooling systems and a god option for CHF prevention purposes. Such nano-suspensions have higher thermal conductivity in comparison with conventional fluids, so they can be utilized for high heat flux applications and as efficient cooling working mediums.

Although the nano-fluids have considerably higher thermal conductivity rather than traditional coolants, fouling formation or deposition of particles on the heating surface is regarded as the major drawback of using these colloid as coolant. Therefore, this has been an incentive for the researchers to conduct investigations on the potential cooling application of nano-fluids. For instance, Bahrami et al. [1] investigated the dynamics of bubbles in pool boiling of nano-fluid with coated and sodium dodecyl sulfate (SDS) solution with different nano-particles. Also, computational fluid dynamics (CFD) module was used for mathematical modeling of bubbles in pure water boiling. Different macro-scale parameters such as: shapes, numbers and contact angle of bubbles also were investigated experimentally and verified by CFD modeling results. Nasr Esfahani [2] performed experiments on nucleate boiling and critical heat flux (CHF) of Fe3O4/ethylene glycol–water nano-fluid at atmospheric pressure on a horizontal thin Ni–Cr wire. The nanoparticles were dispersed in 50% (by volume) ethylene glycol/de-ionized water as base liquid in different volumetric concentrations. Experiments showed that boiling heat transfer coefficients deteriorate by increasing nanoparticle concentration in nano-fluid. Addition of nano-particles delays nucleate boiling incipience and increases critical heat flux (CHF). An experimental study was carried out by Yang and Liu [3] to investigate the pool boiling heat transfer characteristics of functionalized nano-fluid at atmospheric and sub-atmospheric pressures. Experimental results show that there exist great differences between pool boiling heat transfer characteristics of functionalized and traditional nano-fluid. The differences mainly result from the changes of surface characteristics of the heated surface during the boiling. Therefore, the pool boiling heat transfer of nano-fluids is governed by both the thermo-properties of nano-fluids and the surface characteristics of the heated surface. In another study, Song et al. [4] experimentally investigated on boiling characteristic of SiC nano-fluid and evaluated the thermal performance of SiC nano-particles in water pool boiling up to CHF. The volume concentrations of SiC nano-fluid were 0.0001%, 0.001%, 0.01%. The CHF has been enhanced up to 105% for volume concentration 0.01%. CHF enhancement trend was interesting because it did not linearly dependent on nanoparticle concentration. The wettability change of SiC nanoparticle deposited surface was discussed as main reason of CHF enhancement variation. Boiling behaviors of ZnO nano-fluid on a horizontal and vertical plate in saturated pool boiling was experimentally studied by Mourgous et al. [5]. According to the previous researches, it can be stated that CHF enhancement is the obvious consequence of using nano-fluid under the boiling condition. The main reason for this fact can be referred to the fouling formation of nano-particles on the surface, intensification of capillary wicking and also changing in other surface characteristics such as contact angle due to the deposition. Sarafraz et al. [6-10] established experimental studies on fouling formation and heat transfer characteristics of metal oxide nano-fluids and showed that fouling is a negative parameter which influence on bubble formation and heat transfer rate. In fact, depending on the surface roughness and type of nano-particles enhancement/deterioration of heat transfer coefficient can be seen for nano-fluids. Shahmoradi et al. [11] performed experimental studies on nucleate pool boiling of alumina based aqueous nano-fluid on flat plate heater. They demonstrated that for boiling of nano-fluid (< 0.1 vol.%) on heating surface with ratio of average surface roughness to average diameter of particles much less than unity when boiling continue to CHF, the heat transfer coefficient of nano-fluid boiling reduces while critical heat flux (CHF) increases. CHF enhancement increased with volume fraction of nano-particles. Ahn and Kim [12] studied the boiling thermal performance of alumina nano-fluid on a wire and examined the saturated water/alumina nano-fluid pool boiling on a plain copper heater under atmospheric pressure. They compared the boiling characteristics of water and alumina. The unusual boiling characteristics (bending point in the boiling curve at a high heat flux), CHF enhancement, and gradual increase of wall temperature just after the CHF (instead of the rapid increase of wall temperature) were analysed based on high-speed visualizations. Kim et al. [13] conducted an experimental study on flow boiling critical heat flux (CHF) of alumina nano-fluid and alumina coated tubes. The flow boiling CHF of alumina nano-fluid with a plain tube and de-ionized water with an alumina coated tube were enhanced up to about 80% for all experimental conditions. There was no big difference in the CHF results between two methods. The obtained results indicate that the CHF enhancement of alumina nano-fluid is surely caused by deposition of nano-particles on the test section tube inner surface. Lee et al. [14] conducted experiments on the effects of a magnetite-water nano-fluid (MWNF) on the critical heat flux (CHF) enhancement using a Ni–Cr wire in pool boiling. All experiments were performed at a saturated condition under atmospheric pressure. The CHF values between the MWNF and the other nano-fluids with several volume concentrations were compared to evaluate the effect of the MWNF on the CHF enhancement. The CHF values of the MWNF were enhanced from approximately 170% to 240% of pure water as the nanoparticle concentration increased. In addition, the CHF for the MWNF showed the highest value among the evaluated nano-fluids. In most of studies, as can be seen in the literature, nano-fluids can enhance the CHF and sometimes increase the heat transfer coefficient, while there are studies in which deterioration of heat transfer coefficient due to the fouling formation of particles have been reported [15-18].

The main objective of this work is to investigate the influence of presence of TiO_2 nanoparticles on thermal performance of traditional coolant such as water in boiling systems. For this purpose, a set of experiments are performed to quantify the pool boiling heat transfer coefficient of TiO_2 aqueous nano-fluids as a potential coolant. Boiling is performed on a disc heater quenching with TiO_2 nano-fluids at different mass concentrations. Influence of different operating parameters such as applied heat flux to the boiling surface, mass concentration of nano-particles and bulk temperature (sub-cooling level) on the pool boiling heat transfer coefficient of TiO_2 nano-fluids are experimentally investigated and briefly discussed. Since thermal performance of a boiling system strongly depends on bubble formation. Therefore, this phenomenon is visually studied and briefly discussed. Results of this work can be good reference and be a part of general answer to the contraries raised in the literature regarding the pool boiling of nano-fluids.

2 Experimental

2.1 Test rig

Figure 1 presents a schema of experimental setup used for measuring the pool boiling heat transfer coefficient and CHF of CNT nano-fluids. This test rig consists of four main sections: 1) Discoid copper heater as the test section. 2) Auxiliaries including pre-heater, condenser installed inside the test vessel. 3) Temperature measurement instruments including thermocouples,

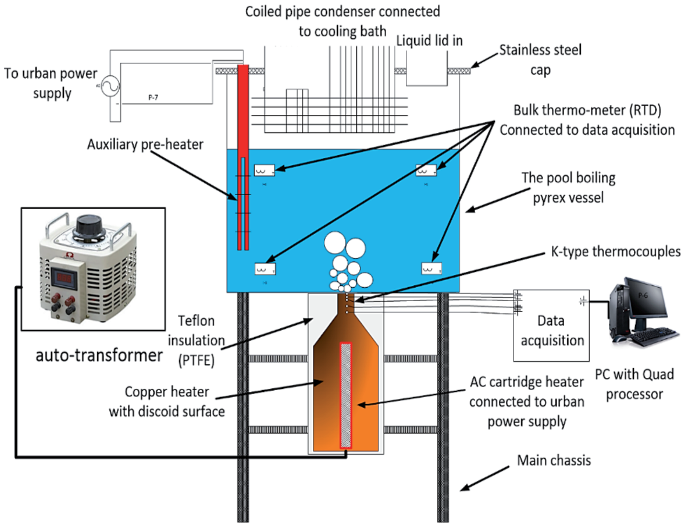

Fig. 1 A schema of experimental rig used for pool boiling CHF

indicators, data acquisition and a post processor (a pc computer). 4) Imaging system including a high-speed camera and a digital microscope with magnification of 500x (IP-U500x).

Nano-fluid is loaded through the inlet port of the test vessel. The vessel is a vertical Pyrex made cylinder, which has enough thermal resistance. In the bottom section of stainless steel cap, there is a perforated hole, in which a discoid copper heater is mounted. A small layer of Teflon is used to prevent from any liquid leakage and heat loss between discoid heater and the hole. This discoid heater consists of a dual diameter cylinder with an axial concentric hole at the bottom, in which a 300 Watt bolt heater is plugged to supply the required heat. The bolt heater power supply is provided by an AC transformer connected to the urban power supply. More details on geometrical properties of discoid heater are given in Fig. 2. The top surface of discoid heater is fixed horizontally inside the cap, so the surface can be used for pool boiling heat transfer and CHF experiments. The surface is circular with outer diameter of 11 mm. In order to measure the temperature of surface, five k-type thermocouples with length of 50 mm and diameter of 1 mm (with precision of ±0.1K) are mounted in the axial holes (with different axial positions) on the upper section of heater. By installing the thermocouples, temperature gradient can accurately be measured, which precisely extrapolates the surface temperature of heater. To minimize the thermal resistance of each thermocouple, holes are filled with silicon paste. The circumference of the heater is heavily isolated by the cylindrical PTFE, (polytetrafluoroethylene) solid to prevent from any heat losses. By heavily isolating the heater, axial heat transfer towards the surface is guaranteed and no radial heat transfer can be seen in heater. To ensure about radial heat transfer, two k- type thermocouples at (r=-0.5, r=+0.5) was mounted to measure the radial temperature distribution. Results showed that temperature at this two points are the same at any given heat fluxes. So radial heat transfer can be ignored. For measuring the liquid bulk temperature, 4 RTDs

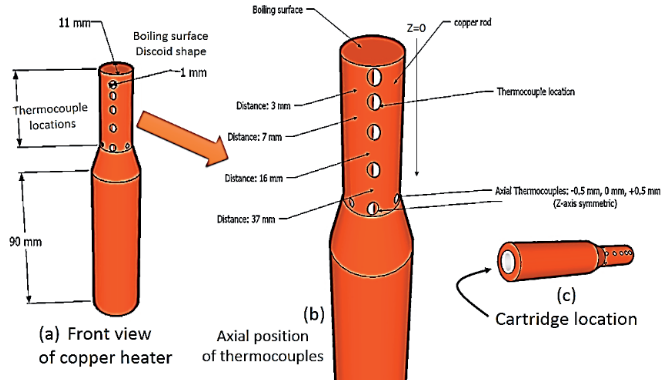

Fig. 2 Details on geometrical properties of discoid heater

(with precision of ±0.1K) are installed at four different locations of test vessel. The arithmetic average of RTD readings is considered as the bulk temperature of vessel. Also, to ensure about saturated boiling, a thermocouple is mounted at the upper part of the vessel to measure the vapor temperature. A pressure transmitter is also installed to record the pressure inside the vessel. A safety pressure valve is connected to the pressure controller and pressure transmitter to control the pressure of vessel. An auxiliary heater is installed inside the vessel to supply the required heat for pre-heating of liquid up to saturation temperature. As soon as nano-fluid temperature reaches to the correspondence saturation temperature and pressure, discoid heater is turned on for starting the pool boiling experiments.

2.2 Nano-fluid preparation and characterization

In order to prepare the nano-fluids, TiO_2 nano-particles were purchased from US-Nano manufacturer. Deionized water was selected as a base fluid. To prepare the nano-fluids, desire weight of nanoparticles were added into the desire weight of deionized water, while it was agitated using stirrer with speed of 200rpm for 30 minutes. Then sodium dodecyl sulfate, SDS was added to the nano-fluid (at 0.1% of general volume of nano-fluid), followed by a sonication process at 400W/20kHz for about 10 minutes. By doing this, the maximum stability of nano-fluids is reported to be about 11 days. Nano-fluids were prepared at wt. %=0.1 to 0.3.

In order to check the morphology and purity of nano-fluids, TEM image (see Fig. 3) and XRD test (see Fig. 4) were provided. As can be seen, nano-particles are spherical, 40-50 nm in size and have similar morphology. In terms of purity, XRD test has provided a unique standard peak, which imply on this fact that there is no impurity in structure of TiO_2 and the Titana phase is anatase.

2.3 Data reduction and uncertainty

The pool boiling heat transfer coefficient is estimated using Eq. (1). Also, it is necessary to extrapolate the boiling surface temperature:

$$h = \frac{q}{T_w - T_b} \tag{1}$$

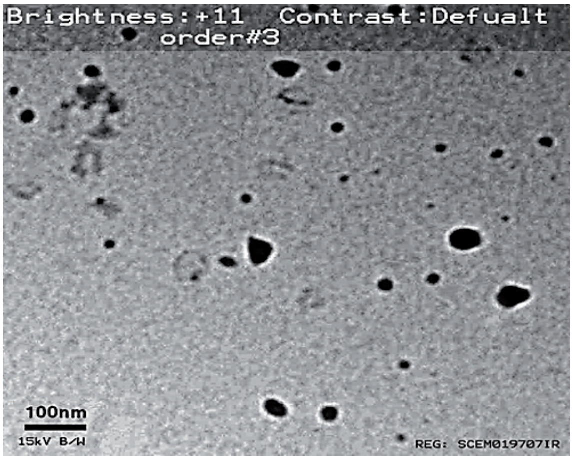

Fig. 3 TEM image of TiO_2

In Eq. (1), T_w is the surface temperature, and T_b is the bulk temperature of liquid, q is the applied heat flux to the liquid from the discoid heater, which can be calculated using Eq. (2):

$$q = -k\frac{dT}{dz}\bigg|_{surface} = -k\frac{T_5 - T_1}{\Delta z_{axial}} \tag{2}$$

Z is the axial direction (see Fig. 2). T1 and T5 are temperatures of location of 1 and 5 respectively shown in Fig. 2. Both are temperatures measured by thermocouples mounted on position 1 and 5 o copper block. Noticeably, according to the Joule's heating effect, heat flux can be directly estimated by Eq. (3) as follows:

$$q = \frac{V \cdot I}{\pi \cdot R^2} \tag{3}$$

In this equation, V is voltage (volt), I is electric current of central heater (Amps) and R is the radius of surface of discoid heater. Circumference of discoid heater has been isolated with PTFE. Therefore, one dimensional conduction heat transfer is the reasonable dominant heat transfer mechanism. Thus, the following linear temperature distribution can be obtained based on Eq. (2):

$$\mathrm{T} = \alpha + \beta z \tag{4}$$

Since at z=0, $T=T_w$, therefore, we have:

$$T_w = \alpha \tag{5}$$

Where, α is the intercept of the line fitted on the measured axial temperatures of discoid heater at a given heat flux. Therefore, alpha can be accurately estimated for each heat flux and is regarded as the surface temperature for each heat flux. A comparison between the heat fluxes estimated from Eq. (2) and that of calculated by Eq. (3) is made to show the quantity of heat loss along with the discoid heater. Fig. 5 shows the results of this comparison. Noticeably, thermocouples and multi-meter were carried out three times to ensure about reproducibility of data. Also, a calibration process using DI-water was performed and results were within ± 9.2% and ± 11.1% for Gorenflo and Rohsenow correlations respectively [5]. It can be stated that at lower heat flux, higher uncertainty was seen (for some data more than 6%), while for high heat flux condition, lower uncertainty was registered. As can be seen in Fig. 5, uncertainty for heat fluxes is lower than 6%, meaning that heat can easily flow from cartridge heater towards the boiling surface and rate of heat loss is reasonable. Figs 6 shows the example of extrapolation calculation for surface temperature using Eqs. (1-5) at

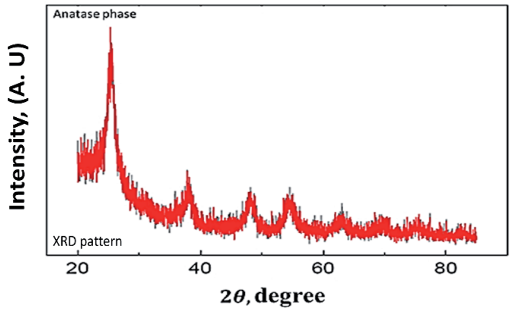

Fig. 4 XRD pattern of TiO_2 nano-particles

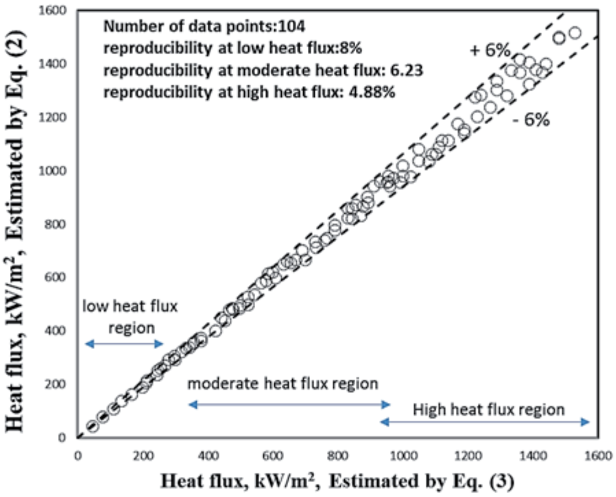

Fig. 5 Heat loss analysis of heater

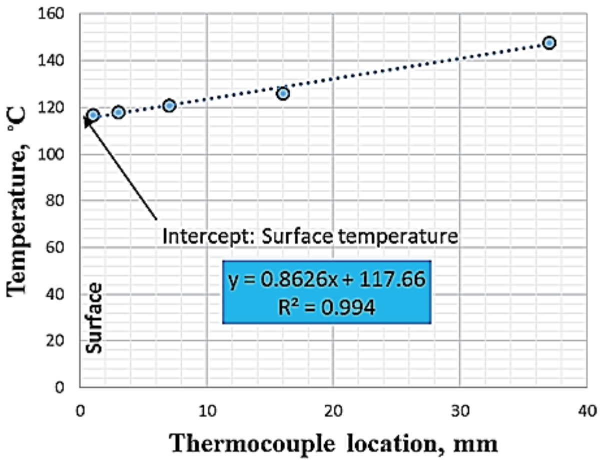

Fig. 6 Prediction of surface temperature for heat flux of 240kW/m² and for DI-water

heat flux 240kW/m^2. This method is performed for each heat flux to estimate the surface temperature with the highest possible R-square (R^2>0.99).

To calculate the uncertainties related to the pool boiling heat transfer coefficient, Kline-McKlintock [19] method has been used, which has been represented as follows:

$$\Delta R = \sqrt{\left(\frac{\partial R}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\Delta x_2\right)^2 + \left(\frac{\partial R}{\partial x_3}\Delta x_3\right)^2 + \dots} \quad (6)$$

In this equation, it is assumed that, R is a given function of the independent variables of $x_1, x_2, x_3, \dots, x_n$, $R = R(x_1, x_2, x_3, \dots, x_n)$, and $\Delta x_1, \Delta x_2, \Delta x_3, \dots \Delta x_n$ are the uncertainties in these independent variables that can be obtained from uncertainty of related instruments. The values of uncertainties can be found in Table 1.

Table 1 Uncertainty values of instruments

Parameters	T	V*	I*	q”	Heat loss	h
Uncertainty(±)	0.3	1%	0.5%	6.5%	6%	10.1%

* V and I are voltage drop and currents which are measured by multi-meter

2.4 Experimental condition

In order to investigate the thermal performance of TiO_2/water nano-fluids, conditions were selected such that to investigate the two distinguishable heat transfer regions namely free convection and nucleate boiling regions. In order to show the influence of TiO2 nanoparticles on heat transfer coefficient, experiments were established at different mass concentrations. Since, most of cooling systems are working under sub-cooled condition (at temperature lower than saturation temperature), therefore, we carried out the experiments under two sub-cooling level (bulk temperature) far from the saturation temperature (70°C and 80°C vs. 100°C), meaning that the temperature of bulk of nanofluid was set in 70°C and once again in 80°C respectively. Table 2 shows the experimental operating conditions.

Table 2 Operating and experimental conditions

Operating parameter	value	SI unit
Heat flux	21-1340	kW/m^2
Mass concentration	0.1%-0.3%	Weight %
Bulk temperature	70, 80	°C

3 Results and discussions

Experimental results on pool boiling of TiO2/water nano-fluids were carried out and influence of different operating parameters on heat transfer coefficient was investigated. Results have been represented in following sections:

3.1 Applied heat flux

With increasing the power throughput of heater, higher heat fluxes are given to the surface. Experimental results showed that with increasing the heat flux, the heat transfer coefficient and the superheat temperature (difference between surface temperature and bulk temperature) considerably increase, however, rate of increase was found not to be linear. Moreover, heat flux has a strong influence on bubble formation such that by increasing the heat flux, rate of bubble formation is significantly intensified. Fig. 7 shows the influence of heat flux on heat transfer coefficient and superheat temperature. Fig. 8 demonstrate the effect of heat flux on bubble formation. Noticeably, images have been taken using high speed video recorder.

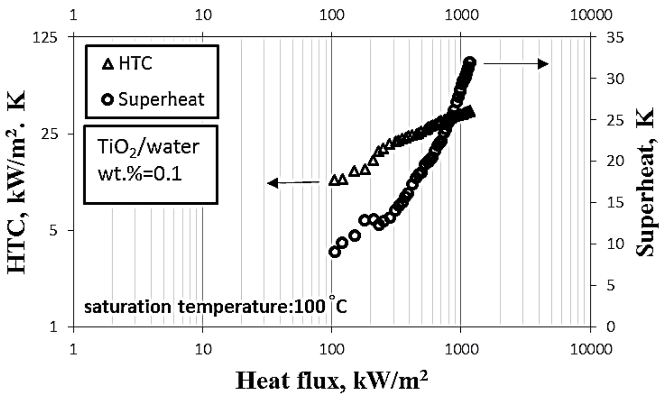

Fig. 7 Influence of heat flux on heat transfer coefficient and superheat temperature for TiO2/water nano-fluids at wt. %=0.1

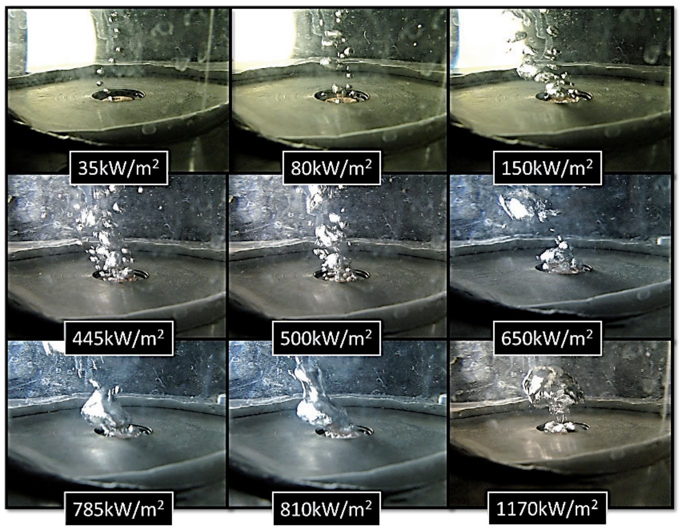

Fig. 8 Bubble formation under influence of heat flux

3.2 Mass concentration of nano-fluids

In order to investigate the effect of mass concentrations, experiments were repeated with three nano-fluids with different mass concentration. Results indicated that mass concentration of nano-fluids can enhance the pool boiling heat transfer coefficient such that at wt. %=0.3 rate of enhancement was 34% in comparison with the base fluid. The reason for this fact can refer to three main reasons.

1. Higher thermal conductivity of nano-fluids due to the presence of solid nano-particles and layer theory.
2. Brownian motion of nano-particles, which facilitate the heat transfer.
3. Deposition of nano-particles on the surface, which intensifies the nucleation sites and bubble formation phenomena.

There is no doubt that nano-fluids have higher thermal conduction over the traditional coolants. But local movement of particles inside the bulk of base fluid can intensify the heat transfer. Since particles can receive the heat near the heating surface and transfer it to the bulk of fluid. Moreover, these particles can deposit on the surface due to aggregation and clustering. These deposition layer provides more nucleation sites on the surface, which leads the bubble formation rate to be improved. Also, this layer is a conductive layer which can transfer the heat to the bulk of fluid though. Noticeably, in the literature, there are studies in which authors have shown that deposition may lead to the heat transfer reduction to the deterioration of surface roughness and contact angle. In this work, our boiling surface roughness is 80 nm (According to the data obtained by roughness meter tester), therefore, roughness of surface and size of particles are in similar range. Subsequently, roughness will remain untouched and no deterioration of heat transfer coefficient can be seen.

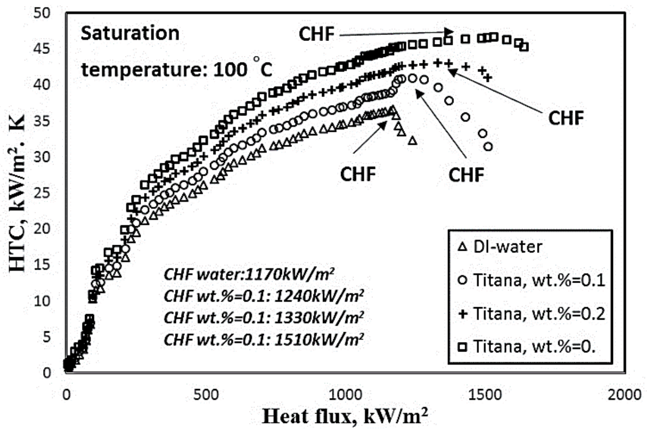

Fig. 9 Influence of mass concentration on heat transfer coefficient.

3.3 Bulk temperature (Sub-cooling level)

As a definition, sub-cooling level is the temperature difference between the boiling surface and bulk temperature of liquid, which is considered as the boiling main driving force. In order to investigate the role of sub-cooling level, the only experimental parameter which can be controlled is bulk temperature. Therefore, experiments were established at two bulk temperatures of 70 and 80°C. Results demonstrated that with increasing the bulk temperature (or decreasing the sub-cooling level), heat transfer coefficient considerably increases. It can be stated that TiO_2 water-based nano-fluids have better thermal performance at higher bulk temperature, meaning that with approaching to the saturation temperature, thermal performance of TiO2 nano-fluid increases, which can be accounted as an advantage for a coolant. Noticeably, at lower bulk temperature, bubble formation is suppressed and mean size of bubbles also reduces, therefore, heat transfer rate decreases due to the deterioration of bubble transport, while at higher bulk temperatures, bubble formation is intensified. Fig. 10 comparatively represents the pool boiling heat transfer coefficient of TiO_2 aqueous nano-fluid at two different bulk temperatures. For other concentrations, similar trend was seen.

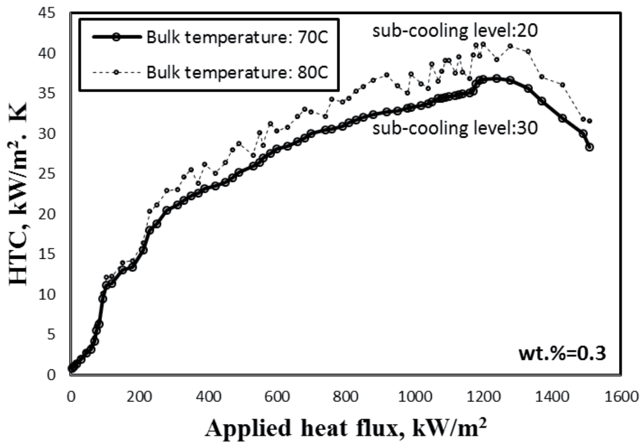

Fig. 10 Influence of bulk temperature on pool boiling of TiO_2 / water nano-fluid at wt. %=0.3

4 Conclusions

Experimental investigations on the pool boiling heat transfer of TiO_2 aqueous nano-fluids were conducted and following conclusions were drawn regarding the TiO_2/water nano-fluid:

Results demonstrated that TiO_2 nano-fluids are promising alternatives for traditional coolants working at boiling conditions. Since this nano-fluid have higher thermal performance at higher bulk temperatures.

With increasing the heat flux and mass concentration of nano-fluids, the pool boiling heat transfer coefficient increases, which leads to the better thermal performance of these nano-fluids. In fact presence of TiO_2 nano-particles enhances the heat transfer coefficient.

Also, heat flux was found to intensify the bubble formation rate. Deposition of nano-particles as the major challenge of application of nano-fluids was seen to have positive impact on the heat transfer coefficient and bubble formation, since deposition can provide more irregularities on the surface and these irregularities can potentially be nucleation sites, which intensify the bubble formation phenomenon.

All in all, although these conclusions are not general to all nano-fluids, presence of TiO_2 nanoparticles inside the water enhanced its cooling performance and can be a promising passive option for improving the thermal performance of systems. Noticeably, more studies are still required to identify the exact role of other nano-particles on pool boiling heat transfer.

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