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RESEARCH ARTICLE

Boiling Heat Transfer of Alumina Nano-Fluids: Role of Nanoparticle Deposition on the Boiling Heat Transfer Coefficient

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Abstract

This paper focuses on the thermal performance of alumina nano-fluids during the quenching process of a surface at the boiling condition, which can be a good answer to the controversial results available in the nano-fluid related literature. For this purpose, an experimental study is conducted to investigate the potential application of alumina/water nano-fluid for cooling a stainless steel rod under the flow boiling heat transfer mechanism. Nano-fluids are prepared by dispersing the 5, 50 and 80nm alumina nanoparticles into the deionized water. The experimental facility provides conditions to quantify the heat transfer coefficient in forced convection and nucleate boiling heat transfer domains at different operating conditions. In terms of operating time, the experiments are divided into two domains namely short time study and extended time study. For the short time study (0-60 minutes of study with neglecting the role of time on the deposition of nanoparticles) enhancement of heat transfer coefficient is reported for all nano-fluids, however for nano-fluid with smaller nanoparticle size, higher thermal performance is registered. In extended time study (60-1000 minutes) heat transfer coefficient is found to be considerably deteriorated for all nano-fluids. This work demonstrates that the reason for deterioration of heat transfer coefficient is referred to the surface roughness, nanoparticle size, static contact angle and thermal fouling resistance parameters. These four parameters are simultaneously determinative factors, which strongly control the thermal behaviour of nano-fluids over the extended time and are the exact reasons for the controversies raised in the literature.

Keywords

flow boiling, particulate fouling, metal oxide nano-fluid, roughness, nucleate boiling, force convection

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1 Introduction

Cooling systems are essential sectors in power cycles and their thermal performances have been an indispensable challenge for heat transfer experts. Working fluid, dominant heat transfer mechanisms and operating conditions are also other major parameters, which strongly influence the quality and efficiency of a cooling system. Nano-fluids, as introduced by Choi [1] are engineered colloids including solid particles with superior thermal conductivity (e.g. metal or none-metal oxide powders) dispersed in traditional coolants such as water, ethylene glycol or oil. Such fluids can be a promising way for improving the heat transfer rate and heat dissipation in heat exchanging media [2-9]. Boiling and two-phase flow phenomena are widely used in different industrial applications such as refrigeration, air-conditioning, heat pumping systems, cooling of high-power electronics components and bio-engineering reactors. Superior heat transfer rate, different controllable sub-phenomena such as bubble transport, nucleation and also complexities encountered in the boiling process have stimulated numerous investigators to conduct extensive researches in this field. The complexities are intensified, when nano-fluid is selected to be a potential coolant in a boiling flow.

Accordingly, many efforts have been made to evaluate the cooling ability of nano-fluids in different boiling conditions. For instance, Kim et al. [10] conducted experiments on boiling and critical heat flux, CHF, characteristics of alumina nano-fluid on plain and nanoparticle coated tubes. Results demonstrated that flow boiling CHF of Al_2O_3 nano-fluid with a plain tube and deionized water with an Al_2O_3 nanoparticle deposited tube were enhanced up to 80% for all experimental conditions. These results indicate that the CHF enhancement of Al_2O_3 nano-fluid is caused by deposition of nanoparticles on the test section tube inner surface. Yang et al. [11] experimented the pool boiling heat transfer of water-based functionalized silica nano-fluids under the sub-atmospheric pressure. Findings 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.

A porous deposition layer exists on the heated surface during the boiling of traditional nano-fluid; however, no layer exists for functionalized nano-fluid. Another nano-fluid-related work conducted by Sheikhbahai et al. [12] demonstrate that for Fe_3O_4/ethylene glycol nano-fluid, porous layer of deposited nanoparticles formed on the heating surface. The maximum CHF enhancement was obtained for 0.1% (by volume) nano-fluid to be about 100% while the boiling heat transfer coefficients deteriorated by increasing nanoparticle concentration in nano-fluid. In another research, the enhancement of pool boiling heat transfer by copper-particle surface coatings is experimentally investigated by Sarangi and his co-workers using free-particle technique [13]. By using this technique, they manipulated the nucleation site densities using loose copper particles which led to enhancing the thermal performance of boiling mechanism. They claimed that free-particle technique is benchmarked against the most traditional technique of sintering a fixed layer of copper particles to the surface to enhance boiling heat transfer performance.

This technique was also shown to offer a straightforward method to screen the boiling enhancement trends expected from different particulate layer compositions that are intended to be subsequently fabricated by sintering. In another article, experimental studies on the nucleate pool boiling of alumina-water based nano-fluids on flat plate heater were performed by Nasresfahani et al. [14]. They showed that, when the heating surface has a ratio of average surface roughness to the average diameter of nanoparticles much less than unity, the heat transfer coefficient of nano-fluid boiling reduces while critical heat flux (CHF) increases. Also, CHF enhancement increased with the volume fraction of nanoparticles. They concluded that changes in boiling surface topology and thermal resistance of heater surface due to nanoparticle deposition can lead to variations in nano-fluids boiling performance. Khoshmehr et al. [15] investigated the quenching of a silver rod at two different surface roughness values by DI-water and carbon nanotube/DI water nano-fluid as coolants. They observed that for identical circumstances by repeating the test, the quenching time of the sample in both deionized water and CNT nano-fluid decreased.

The comparison between the two surface roughness values revealed that the cylinder with higher surface roughness quenched faster and roughness had a significant effect. The subsequent test was conducted in order to investigate the effect of surfactant dissolved in deionized water. Results indicated that the quenching time increased. Lee et al. [16] performed experimental investigations on flow boiling CHF of graphene oxide, (GO) nano-fluid. experiments were carried out for round tubes with 0.5 inch nominal diameter and 0.5 m heating length under low pressure and low flow (LPLF) at two fixed inlet temperatures (25 and 50 °C) and at four different mass fluxes. It was found that the CHF of the GO/water nano-fluid was enhanced about 100% in comparison with those of experimentally measured for base fluid. In our previous studies [16-20], it was found that boiling heat transfer coefficient as a thermal performance criterion can be deteriorated up to 40% for nano-fluids over the extended time. More importantly, deposition of nanoparticles on the heating section can change the surface characteristics, which influences on the roughness and subsequently, the number of nucleation sites. Hence, bubble formation is strongly under the influence of deposition of nanoparticles on the surface.

Beside, the stability of nano-fluids was found to be another important parameter, which should carefully be considered in boiling experiments. In this work, the influence of operating parameters including the heat and mass fluxes, the mass concentration of nano-fluids and size of nanoparticles on thermal performance of alumina nano-fluids are investigated and discussed with considering the effect of nanoparticle deposition. In terms of heat transfer mechanism, studies are conducted at two different heat transfer domains namely forced convection and nucleate boiling. Since time is a key parameter in fouling-related studies, therefore, experiments are established in short time study (60 to 1000 min) and extended time study (less than 60min, when no fouling is observed on the rod), which leads to the interesting results about boiling thermal performance of nano-fluids. Results of this research is a good answer to the existing contraries in the literature about thermal behavior of nano-fluids in boiling condition and can open a new horizon for determining the exact role of particulate fouling on the thermal performance of nano-fluids.

2 Experimental

2.1 Experimental setup and data reduction

A scheme of the experimental setup used in this work has been shown in Fig. 1a. The test rig consists of three main sections comprising the temperature measurement instruments, main test section, which is an annulus space, fluid flow loop including the pump, pipes, flow meter and fluid tank. The working fluid enters the loop from a tank through the isolated pipes and is continuously circulated by a centrifugal pump (DAB Co.). An ultrasonic flow meter is installed in the trajectory line of fluid to measure the flow rate. The fluid temperature at inlet and outlet of test section was measured by two PT-100 thermometers (RTDs) installed in two thermo-well located just before and after the annular heat exchanger (T_{in} and T_{out}). The complete cylinder was made from stainless steel. Thermometer voltages, current and voltage drop from the test heater were all measured and processed with a data acquisition system in conjunction with a PID temperature controller. The test section is shown in Fig. 1b consists of an electrically heated cylindrical DC bolt heater (manufactured by Cetal Co.) with a stainless steel surface, which is mounted concentrically within the surrounding pipe. The dimensions of the test section are: diameter of heating rod, 21 mm and its length 150 mm; annular gap diameter (hydraulic diameter) 30 mm; the length of the Pyrex tube is 200 mm; the; the length of heated section, 100 mm which means that just the first 100 mm of stainless steel is heated uniformly and radially by the heater. The axial heat transfer through the rod can be ignored according to the insulation of the both ends of the heater. The heat flux and wall temperature can be as high as 175kW.m^{-2} and 163°C, respectively. The wall temperature local wall temperatures have been measured with four stainless steel K-type thermocouples (diameter of 1.5 mm and length of 80mm), which have been installed near the heat transfer surface. The temperature drop between the thermocouples location and the heat transfer surface can be calculated from:

$$T_w = T_{th} - q^{"} \frac{s}{k} \tag{1}$$

T_w is surface temperature, q" is given heat flux, which can be calculated by Eq. (2):

$$q^{"} = \frac{V \cdot I}{2\pi r L} \tag{2}$$

V is the applied voltage to the central heater by an auto-transformer, I is the current measured by a multimeter, L is the length of the cylinder, r is the radius of the cylinder, s is the distance between thermocouple local and surface, and k is thermal conductivity of stainless steel. The ratio between the distance of the thermometers from the surface and the thermal conductivity of the tube material (s/k) was determined for each K-type thermocouple by calibration using Wilson plot technique [21]. Note that, all the K-type thermocouples were thoroughly calibrated using a constant temperature water bath, and their accuracy has been estimated to ±0.3K.

The local heat transfer coefficient, α is then calculated from:

$$\alpha = \frac{\rho V_f C_{p,nf}\left(T_{out} - T_{in}\right)}{\left(T_w - T_b\right)_{av}} \tag{3}$$

T_w is the boiling wall surface, which is the arithmetic average of temperature readings from the four K-type thermocouples mounted around the circumference of the rod. T_b is the bulk temperature, which is estimated by the arithmetic average of inlet and outlet temperatures. V_f is fluid flow rate, ρ and C_p is density and the specific heat of the fluid. In order to minimize the thermal contact resistance, high-quality silicone paste was injected into the thermocouple wells. To avoid possible heat loss, main tank circumferences were heavily insulated using industrial glass wool. To control the fluctuations due to the alternative current, a regular DC power supply was also employed to supply the needed voltage to the central heater. Likewise, to visualize the flow and boiling phenomenon and record the proper images, annulus was made of the Pyrex glass. Figure 1b shows the heating section and thermocouple locations.

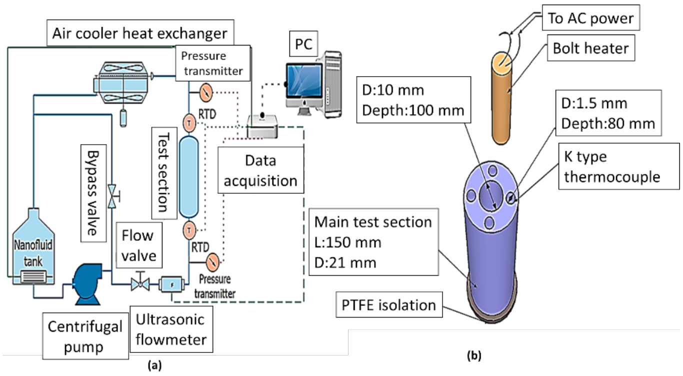

Fig. 1 a) A schema of test rig used in this work, b) details of the test section.

2.2 Uncertainty analysis

The uncertainties of the experimental results are analyzed by the procedures proposed by Kline and McClintock [22]. The method is based on the careful specifications of the uncertainties in the various experimental measurements. According to Eq. (3), the uncertainty in the measurement of the heat transfer coefficient can be related to the errors in the measurements of volume flow rate (V_f), hydraulic diameter, and all the temperatures as follows:

$$\alpha = f\left\{V_f, A_h, \left(T_{out} - T_{in}\right), \left(T_w - T_b\right)\right\} \tag{4}$$

$$\partial\alpha = \sqrt{\left[\left(\frac{\partial\alpha}{\partial V}\right)\cdot\delta V\right] + \left[\left(\frac{\partial\alpha}{\partial A}\right)\cdot\delta A\right] + \left[\left(\frac{\partial\alpha}{\partial\left(T_{out}-T_{in}\right)}\right)\cdot\delta\left(T_{out}-T_{in}\right)\right] + \left[\left(\frac{\partial\alpha}{\partial\left(T_w-T_b\right)}\right)\cdot\delta\left(T_w-T_b\right)\right]^2} \tag{5}$$

According to the above analysis, estimated the uncertainty of heat transfer coefficient is 16.23%. The detailed values for the uncertainty of instruments are presented in Table 1. The main source of uncertainty is due to the temperature measurement and its related devices.

Table 1 Uncertainties of measurement instruments

Parameter	Uncertainty
Length, width and thickness, (m)	$\pm 5\times10^{-5}$
Temperature, (K)	±0.3K
Water flow rate, (lit·min^{-1})	±1.5% of readings
Voltage, (V)	±1% of readings
Current, (A)	±0.02% of readings
Cylinder side area, (m^2)	$\pm 4\times10^{-8}$
Flow boiling heat transfer coefficient, (W/m^2·K)	±16.23 %

Noticeably, at each given heat flux, temperature readings are registered after 5 minutes to ensure the stability of values. Also, experiments were performed three times to ensure about reproducibility.

2.3 Nano-fluid (NF) preparation

Alumina nanoparticles (purchased from US-nano) at three different particle sizes of 5nm (NF#1), 50nm (NF#2) and 80nm (NF#3) were uniformly dispersed into the deionized water as base fluid at two different volumetric concentrations of 0.5% and 1%. Ultrasonic Hielscher 400W/24 kHz was implemented for about 15 minutes to crack the agglomerations and clusters. As a dispersant, Sodium dodecyl sulfate, SDS was employed at 0.1% of the general volume of nano-fluid to have the least impact on the thermo-physical properties of nano-fluids. To ensure the quality of dispersion, morphology and size of nano-particles, transmission electron microscopic images (TEM) were taken from the samples. According to TEM images, nano-particles are almost spherical and in a good agreement with the size claimed by the manufacturer. Figure 2 represents the TEM images belonging to prepared NFs.

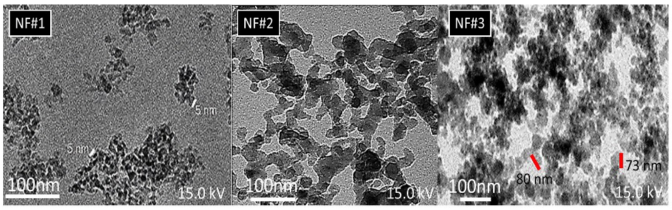

Fig. 2 TEM images of prepared nano-fluids

3 Results and discussions

Results demonstrated that in terms of the mechanism involved, two distinguishable heat transfer domains can be observed for flow boiling heat transfer namely: convective and nucleate boiling heat transfer domains. In the convective region, heat transfer coefficient is drastically lower than that of nucleate boiling due to the sub-phenomena involved in nucleate boiling mechanism e.g. bubble formation. In fact, bubble transport is a considerable sub-phenomena comprising evaporation, micro/macro convection mechanisms induced by generated bubbles from the surface and subsequently condensing the bubbles inside the bulk of the liquid, which drastically enhance the heat transfer coefficient.

Therefore, relatively higher heat transfer coefficient is obtained for nucleate boiling region (see Figs. 3 and 4). For nano-fluids, due to the evaporation of base fluid, micro-layer close to the heating surface is concentrated at the time and subsequently, particles are found to have more tendency for depositing on the surface. Such depositions can form micro-cavities and structures on the surface, which apparently can enhance the heat transfer coefficient. However, in the literature, there are studies, in which deterioration of heat transfer has been reported. To find the exact reason, experiments have been established on the flow boiling of nano-fluids to investigate the potential impact of nanoparticle deposition. A criterion for measuring the fouling is defined as [23]:

$$R_f = \frac{1}{\alpha[t]} - \frac{1}{\alpha_{clean}[t=0]} \quad (6)$$

In Eq. (6), α is flow boiling heat transfer coefficient, R_f is fouling resistance and t is the operating time, in which heat transfer coefficient is measured. According to Eq. (6), heat transfer coefficient can be measured at the initial time of the experiment, when no fouling can be observed on the surface (t=0). The measurement should be repeated once again at times greater than 60 minutes. Therefore, experiments are conducted in two-time domains. The first domain is short time study (0-60 min), in which role of time is neglected, and no fouling can be observed on the surface. The second domain is extended time study (next 60-1000 min), in which role of time is considered when fouling is clearly formed on the surface. Results of experiments are briefly discussed in following sub-sections.

3.1 Short time study (steady state)

In this domain, no fouling is formed on the surface. Therefore, the only criterion for assessing the thermal performance of nano-fluids is the heat transfer coefficient, (HTC). Results demonstrated that NF#1 has higher heat transfer coefficient in comparison with other nano-fluids. Because, NF#1 has the significantly higher specific surface area, which facilitates the heat transfer due to its enormous available specific surface and higher thermal conductivity [24, 25]. Figures 3 and 4 comparatively present the heat transfer coefficient for three nano-fluids in forced convection and nucleate boiling domains in short time study. As can be seen, for both mechanisms, when nanoparticle size decreases, the heat transfer coefficient significantly increases.

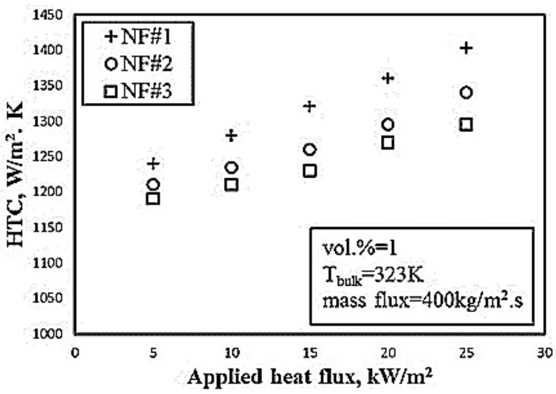

Fig. 3 Experimental heat transfer coefficient of nano-fluids in forced convection domain and for short time study.

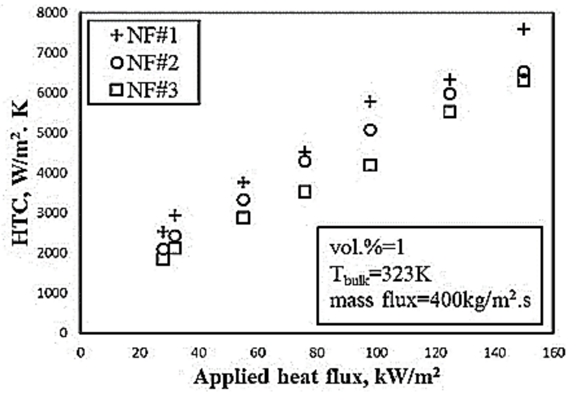

Fig. 4 Experimental heat transfer coefficient of nano-fluids in the nucleate boiling domain and for short time study.

In flow boiling heat transfer, the fluid flow rate has a significant role on the system thermal performance. In fact, the hydrodynamic velocity is found to have a strong influence on the heat transfer coefficient of nano-fluids. In terms of fluid velocity (flow rate), as represented in Fig. 5, it can be stated that, by increasing the flow rate, higher heat transfer coefficient is obtained for both heat transfer mechanisms. By involving the influence of nano-fluid concentration, it is found out that higher heat transfer coefficient can be observed, when the volumetric concentration of nano-fluid increases. These trends can be seen for other test nano-fluids and for both heat transfer mechanisms and time domains. Figure 5 shows the influence of fluid velocity on the thermal performance of NF#1 nano-fluid.

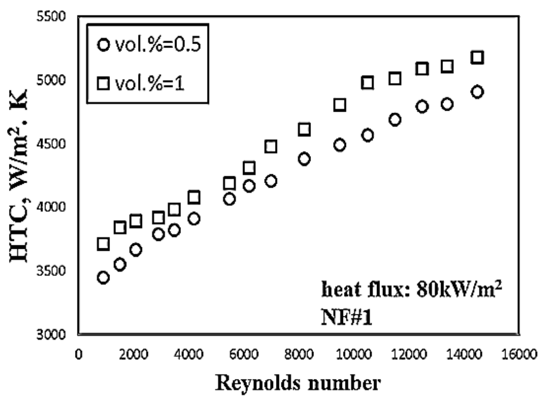

Fig. 5 Influence of hydrodynamic velocity (flow rate) on heat transfer coefficient (HTC) at different volumetric concentrations.

Noticeably, for pressure drop, particularly in forced convection region, results showed that nano-fluid with higher nanoparticle size has a higher pressure drop, which is in accordance with the previous works [8]. Study on the pressure drop of nano-fluids is out of goals of this work.

3.2 Extended time study (unsteady state)

In extended time study, the role of fouling become more important and determinative. When fouling is formed on the surface, two possible cases can be considered. In the first case, the ratio of mean nanoparticle size to the average roughness of the surface is much more than unity [14] and in the second case, the ratio of nanoparticle size to the roughness of the surface is less than unity [25, 26]. In this work, three nano-fluids with different particle size are utilized. Conveniently, a parameter is defined as the ratio of nanoparticle size to surface roughness (NS/SR).These two parameters have been introduced as major factors, which can control the boiling behavior of nano-fluids, while measuring the fouling resistance and changes in static contact angle due to the fouling has been ignored there.

Nanoparticle size and surface roughness are characteristics of particulate boiling systems, while changes in static contact angle and thermal fouling resistance are parameters depending on the time of operation and should carefully be considered. Experimental data demonstrate that heat transfer coefficient can be deteriorated over the extended time, due to the significant thermal resistance created on the heating surface. Deposition can cause the increase of fouling resistance (estimated by Eq. (6)) during deterioration of heat transfer coefficient [19, 28]. To interpret this phenomenon, it can be stated that, in boiling micro-layer, nano-fluid is concentrated due to the evaporation of bulk of base fluid. Therefore, fouling due to the sedimentation of nanoparticles, aggregations and clustering can be formed. It can also be stated that formation of fouling can change the irregularities and micro-cavities on the surface.

Depending on the NS/SR value, the rate of fouling on the surface can be different and subsequently, deterioration of HTC can have various rates for nano-fluids. In our work, NF#1 has lower fouling in comparison with other nano-fluids. For NF#1, nanoparticles are smaller, therefore, their apparent density due to the aggregations is lower than other nano-fluids. Subsequently, NF#1 has a lower gravitational settlement of nanoparticles in boiling micro-layer. This can be interpreted by Stokes' law indeed. According to Stokes' equation, the sedimentation rate, v in a colloid liquid can be expressed as follows:

$$v = \frac{R^2}{9\mu} \cdot \left(\rho_p - \rho_l\right) \cdot g \qquad (7)$$

As can be seen in Eq. (7), the rate of sedimentation decreases by decreasing the particle size. Noticeably, for this equation, it is assumed that particles are spherical, so their size is expressed by R (radius); g is gravity; $(\rho_p - \rho_l)$ is density difference between the nanoparticle and the base liquid, μ is base fluid viscosity. Figure 6 presents the heat transfer coefficient of nano-fluids in the nucleate boiling region over the extended time. For all NFs, the rate of deterioration is non-linear. For forced convection region, similar trends were seen for all nano-fluids. Also, for nano-fluids with larger particles, higher deterioration rate can be seen for heat transfer coefficient.

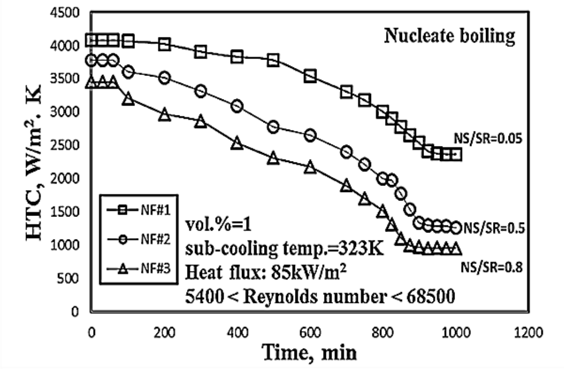

Fig. 6 Reduction of heat transfer coefficient due to the fouling formation in extended time study

Figure 7 shows the thermal fouling resistance of nano-fluids in flow boiling. As can be seen, fouling resistance is a strong function of time such that with increasing the time, higher fouling resistance is measured. Likewise, for nano-fluids with larger particles, fouling resistance can be as high as 3.43 while for NF#1 with smaller particle size, fouling resistance is approximately 2. Therefore, an increase of nanoparticle size can intensify the fouling resistance of nano-fluids, which directly decreases the heat transfer coefficient due to the thermal resistance.

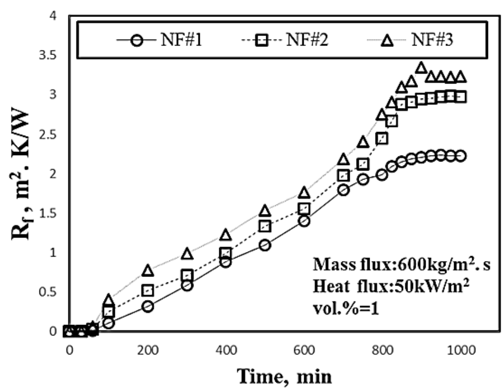

Fig. 7 Fouling resistance of different nano-fluids

Studies on the surface morphology and roughness of surface show that by increasing the NS/SR, thermal fouling resistance considerably increases, which enhances the roughness of the surface. However, according to the results, it can be seen that boiling heat transfer coefficient does not depend on to the roughness solely. In fact, a deposition layer of particles can change the surface tension and surface forces on the boiling surface such that static contact angle of liquid drops can considerably change. Therefore, a visual study is established using IPU500x digital microscope to visually measure the liquid drop contact angle of nano-fluids. Noticeably, bubble transport is the main sub-phenomena, which considerably influence the heat transfer and thermal performance of liquids. In order to intensify the bubble transport, a number of nucleation sites should be enhanced. When to contact angle of liquid drop decreases, the drop will lie down on the boiling surface and subsequently, possible nucleation sites are filled with liquid and as the result, bubble formation sub-phenomena considerably suppresses. All the explained mechanisms lead the heat transfer coefficient to be decreased over the extended time. Briefly speaking, boiling heat transfer coefficient is a strong function of micro-cavities and micro-structures of surface and contact angle of liquid as well, meaning that roughened surfaces are favorable for boiling heat transfer [27] if they provide higher contact angle and extensive micro-cavities.

Figure 8 demonstrates the measured static contact angle of a 1μl liquid drop on the boiling surfaces. As can be seen, for NS/SR=0.8 (the largest nanoparticles), the static contact angle is the lowest, meaning that liquid drop lies down on the surface and fills the nucleation sites, subsequently, less bubble can be formed on the surface and bubble formation suppresses. Interestingly, the lower contact angle can be seen for the surface with higher fouling resistance with thicker deposition layer. All in all, roughness in not the determinative parameter. Because as can be seen in Fig. 8, at the smoother surface, higher heat transfer coefficient is obtained, which is due to the contact angle of a liquid drop on the deposited surface. This is why higher heat transfer coefficient is seen on smoother surface and for smaller nanoparticles. Briefly speaking, roughness and thermal fouling resistance are not determinative parameters and role of nanoparticle size and deposition on static contact angle should carefully be considered to predict the boiling behavior of nano-fluid under the boiling condition.

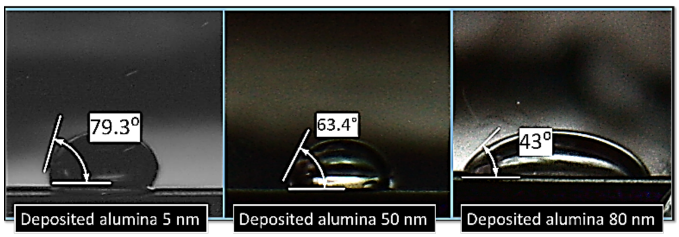

Fig. 8 Static contact angles for deposited surfaces after boiling experiments and for alumina/water at vol. %=1.

4 Conclusions

Experimental studies on the flow boiling heat transfer of alumina/water nano-fluids were conducted and following conclusions have been made:

- In terms of heat transfer mechanism, forced convection and nucleate boiling were two involved dominant mechanisms, in which heat transfer coefficient has different values such that for the nucleate boiling mechanism, significantly higher heat transfer coefficient can be obtained due to the bubble transport sub-phenomena.
- In terms of operating time, two main regions should be considered namely short and extended time studies. In short time investigation, it can be seen that the heat transfer coefficient of nano-fluids can be increased by increasing the heat and mass fluxes and concentration of nano-fluids as well and also by decreasing the nanoparticle size.

- For the extended study, the heat transfer coefficient has a complicated behavior. Although roughness of the surface is the favorable parameter for enhancing the heat transfer coefficient, fouling resistance and static contact angle have more important roles such that on the deposited surface with a lower contact angle, the number of nucleation sites decreases and as the result, bubble transport become weaker, which can deteriorate the heat transfer coefficient. Results also demonstrated that nano-fluids with larger particles can provide a surface with lower contact angle. Therefore, lower heat transfer coefficient can be obtained for such surfaces. These points have been ignored on some of nano-fluid boiling–related literature and cause controversies regarding the thermal performance of nano-fluids under boiling condition.

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