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# Critical heat flux and pool boiling heat transfer analysis of synthesized zirconia aqueous nano-fluids

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ABSTRACT

In this work, experimental investigation on the pool boiling heat transfer to zirconium oxide nano-fluids was carried out. Zirconium oxide was prepared using chemical sol-gel method. Characterization of synthesized nano-particles was performed using scanning electron microscopic, x-ray diffraction and particle size count tests. The obtained nano-powders were then dispersed in water–ethylene glycol mixture 50:50 as a base fluid at volumetric particle concentrations of 0.025%, 0.05%, 0.075%, and 0.1%. Before boiling experiments, thermal conductivity of zirconium oxide was experimentally measured at different weight percentages. Results demonstrated that pool boiling heat transfer coefficient can be enhanced up to 12% at vol. % = 0.1. A very slight particle deposition was also observed on the surface after boiling experiments, which had no impact on heat transfer coefficient, but to enhance the critical heat flux value up to 29%. Surface characterization demonstrated that static contact angle of liquid drop on the surface decreases by forming the thin deposition layer on the surface, which increases the wettability and capillary wicking action as well. Roughness of surface was found to be increased due to the deposition of nano-fluids too.



## 1. Introduction

Boiling heat transfer is one of the hot-debated topics and has been regarded as one of the major interests of the heat transfer experts. Due to the complexities encountered in boiling-related studies, still there are many efforts toward the understanding the governing mechanism and exact behavior of coolant in boiling conditions. When boiling comes to the nano-fluids (colloidal suspensions comprising solid particles with mean size of 0–100 nm dispersed in a traditional coolant such as water or ethylene glycol), complications are intensified, since nano-fluids can lose their stability and form a deposition layer on the surface due to the evaporation of base fluid. This behavior can change the surface characteristics, which lead the thermal performance of nano-fluid to be changed. Another important influence of nano-fluid deposition can be found on the critical heat flux crisis. Critical heat flux (CHF crisis) 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 the surface or explode the heater, since heat cannot be transferred properly from the surface toward the bulk of coolant. A nucleate boiling system is comprised of three main heat transfer mechanisms: (1) heat conduction through liquid from the boiling surface to the liquid–vapor equilibrium interface, (2) evaporation at the liquid–vapor interface toward the vapor phase, (3) departing the vapor from the heating surface in form of bubble and vapor blanket depending on the applied heat flux. The critical heat flux phenomena occur when either generation or escape of vapor is restricted or hindered. In terms of boiling heat transfer coefficient, there are evidences showing that presence of nano-particles can enhance the boiling performance [1–7], there are still others who back up the notion that boiling heat transfer can be deteriorated in nano-fluids [8–12]. These controversial opinions are a huge motivation for studying the boiling heat transfer in different conditions and for different nano-fluids to find a general answer. For example, in an experimental work conducted by Fan et al. [13], stainless steel spheres in dilute aqueous graphene oxide, (GO) nano-sheets nano-fluids at various concentrations (by weight) up to 0.1 wt.% were quenched. The experiments were performed for saturated boiling and boiling curves were obtained for the nano-fluids in comparison to the baseline case of pure water. It was shown that quenching is accelerated upon increasing the concentration of nano-fluids. The enhanced boiling heat transfer by the nano-fluids was interpreted in relation to the modified surface properties, including morphology, wettability, and roughness, on the quenched surfaces. Sarafraz et al. [14–16] established experiments on thermal performance of alumina and copper oxide nano-fluids in a boiling pool. They demonstrated that pool boiling heat transfer can be deteriorated over the extended time, since nano-particles can form a fouling layer on the surface, which causes a significant thermal resistance. Tang et al. [17] performed a set of experiments on pool boiling heat transfer characteristics of gamma alumina/R141b nano-fluids on a horizontal

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**Nomenclatures**

| | |
|---|---|
| H | Heat transfer coefficient, $kW/m^2$. K |
| I | Current, Amper |
| K | Thermal conductivity, W/m. K |
| Lc | Capillary characteristic |
| Q | Heat flux, $kW/m^2$ |
| R | Heater radius, m |
| S | Microstructure wall space, m |
| T | Temperature, K |
| V | Voltage, volt |
| Z | Axial distance, m |

*Greek letters*

| | |
|---|---|
| $\rho$ | Density, $kg/m^3$ |
| $\sigma$ | Surface tension, N/m |
| $\theta$ | Contact angle, degree |

*Abbreviations*

| | |
|---|---|
| CHF | Critical heat flux |
| DIW | Deionized water |
| HF | Heat flux |
| HTC | Heat transfer coefficient |
| WEG50 | Water–ethylene glycol 50:50 mixture |

flat square copper surface at heat fluxes ranged from 10 to 200 $kW/m^2$. The surface roughness has been controlled by sandpaper of grade #2000 before boiling. The results show that the presence of alumina nano-particles can enhance or deteriorate the pool boiling heat transfer coefficient, which strongly depends on the concentration of nano-particles dispersed in base fluid. In another study, nucleate boiling heat transfer of alumina–water–ethylene glycol nano-fluids under atmospheric pressure was investigated by Raveshi et al. [18]. He and his co-workers evaluated six different volume fractions of the nano-fluids to study the impact of concentration on boiling heat transfer of binary mixture of water/ethylene glycol based nano-fluids. The results showed the high effectiveness of the nano-particles on heat transfer coefficient. In addition, the experimental results indicated that there is an optimum volume concentration of nano-particles, in which the heat transfer coefficient has its maximum value. Furthermore, the optimum volume concentration of nano-particle and the maximum increment of boiling heat transfer coefficient in their study were 0.75% and 64%, respectively. In abovementioned researches, nano-fluids have been supplied by a manufacturer, dispersed in to a base fluid, and stabilized using post chemical treatment such as surfactants, dispersants, or pH control methods. In this work, special attention has been paid to the zirconia and its potential application(s) in thermal systems. For this purpose, synthesized zirconium oxide is added into the water–ethylene glycol 50:50, WEG50 for enhancing its thermal features, while zirconia is produced using sol-gel method, and then dispersed into the base fluid without any additives or chemical surfactants. Pool boiling heat transfer characteristics of prepared nano-fluids are then experimentally investigated and compared to tradition WEG50 coolant. Results of this work interestingly show that this nano-fluid not only have wide applications in chemical reactions and catalytic industries but also may be utilized in advanced thermo-fluid and engineering systems as a coolant.

## 2. Experimental

### *2.1. Material and nano-fluid preparation*

In order to produce the zirconium oxide, ($ZrO_2$) the sol-gel method was implemented. For this purpose, 300 ml of butoxide zirconium as a precursor was dissolved in pure ethanol in a clean flask at room temperature, while the mixture was agitated by a stirrer at speed of 100 rpm. In order to produce the gel, deionized water was then added into the mixture and constantly heated at 300 °C. The obtained gel was dried for 24 hours by a microwave-assisted dryer set at 100 °C. As a post treatment, the product was calcined by a furnace with rate of 3 °C/min up to 400 °C for 4 hours. The final product was crushed, grinded, and screened using 60/80 mesh screen. Quality tests were then carried out to ensure about the morphology, size, and quality of zirconium oxide nano-particles. Results of quality tests have been described in Section 2.2. To prepare the nano-fluid, desired mass of $ZrO_2$ was added into the weighted base fluid. For 10 minutes, each nano-fluid was exposed to sonication process using ultrasonic (400 W/20 kHz) to homogenously disperse the nano-particles within the base fluid. Nano-fluids were prepared at weight percentages of 0.025%, 0.05%, 0.075%, and 0.1%. Nano-fluids were prevented from adding any surfactants, since nano-particles have been produced using synthesis technique and surfactant can drastically change the thermo-physical properties of nano-fluids. No sign of settlement or deposition was seen after 1 week of preparation.

### *2.2. Quality tests*

When nano-particles were produced, morphology, size, and purity of them were precisely determined thanks to the scanning electron microscope (SEM), X-ray diffraction (XRD), and particle size count (PSC) test using digital light scattering instruments. Fig. 1 (a–c) demonstrates the results of quality tests. Fig.1a shows the SEM image taken from the nano-particles. As can be seen, particles are almost spherical, identical in size, and have similar color. Fig.1b represents the XRD pattern belonging to zirconia. As can be seen, peaks of broad due to the nano-sized effect. Moreover, no external/unknown peak is detected by XRD, meaning that there is no impurity in the structure of nano-particles. Also, molecular structure (shape phase) of zirconium oxide was found to be cubic. This structure, due to its symmetric bonds, has higher thermal conductivity rather than other molecular structures, which is suitable for heat transfer applications. Fig.1c shows the particle count size test. As can be seen, the dominant particle size is 20–25 nm which is in accordance with SEM image.

### *2.3. Experimental setup*

Fig. 2 shows a schema of the experimental setup used in this work. 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, indicators, data acquisition, and a post-processor computer. (4) Imaging system including a high-speed camera and a digital microscope with magnification of 500× (IP-U500×). Nano-fluid is loaded through the inlet port of the test vessel. The vessel is a vertical Pyrex 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 inserted to supply the required heat for boiling experiments. The bolt heater power supply is provided by a 0–300 volt AC transformer connected to the urban power supply. Detailed geometrical specifications of discoid heater have been given in Fig. 3. 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 calibrated k-type thermocouples with length of 50 mm and diameter of 1 mm (with precision of $\pm 0.1$ *K*) are mounted in the axial holes (with different axial positions) on the