Experimental study of heat transfer characteristics of nanofluids nucleate and film boiling on horizontal flat plate

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Abstract

In this paper, the heat transfer characteristics of nanofluids nucleate and film boiling is studied experimentally. For this purpose, Al₂O₃ and SiO₂ deionized water-based nanofluids prepared with three volumetric concentrations of 0.1%, 0.3% and 0.5%. The boiling experiments were conducted on a circular and polished copper surface with a diameter of 25 mm. The results showed that the addition of nanoparticles to the base fluid reduced the heat transfer coefficient of nucleate boiling. The boiling of nanofluids increased the surface wettability and the critical heat flux was significantly higher than that of pure deionized water. The Al₂O₃ deionized water-based nanofluid with a volumetric concentration of 0.5% had the best performance, with a critical heat flux of 44.56% higher than that of pure deionized water. The presence of nanoparticles in the deionized water-based nanofluid improved the heat transfer coefficient of film boiling. The results showed that the stable film boiling for nanofluids starts at higher wall superheat temperature difference than pure deionized water. Among the investigated concentrations, volumetric concentration of 0.5% had best performance for both nanofluids, so that the minimum heat flux of Al₂O₃ and SiO₂ deionized water-based nanofluids were increased 35.01% and 34.40% compared to pure deionized water, respectively.

Keywords: Nucleate boiling, Film boiling, Critical heat flux, Minimum heat flux, Nanofluids.
1. Introduction

Among the various methods of heat transfer, the use of boiling phenomenon due to its high thermal efficiency is widely used in various industries such as power plants, chemical industries, refrigeration and air conditioning systems. In these industries, flat or curved geometric surfaces are used horizontally, vertically, and inclined as the boiling surface, among which, boiling on horizontal surfaces has a special application in cooling of electronic systems, heat exchangers, and boilers. The growing need for these industries, and the need to increase their efficiency, has led researchers to focus on improving cooling and heat transfer. The main problem in the use of boiling phenomenon is the existence of high and uncontrolled temperatures in the heat transfer devices, which limits the choice of material in these devices. Reforms that increase the efficiency of these systems have great importance in energy saving. Therefore, the study of methods to improve the boiling phenomenon has been the focus of researchers for many years. Different techniques have been proposed to improve the boiling process. One of which is the addition of nanoparticles to the base fluid.

The results based on the dispersion of nanoparticles help engineers design an efficient thermal system [1]. The presence of nanoparticles in the base fluid can improve some of the thermal and thermophysical properties of the fluid. In the pool boiling of nanofluids, the addition of nanoparticles to the base fluid increases the specific surface area. On the other hand, the Brownian motion of the nanoparticles increases the turbulence and mixing in the fluid, which leads to an increase in thermal conductivity. Because nanoparticles are primarily made of metals or metal oxides, they have higher thermal conductivity compared with base fluids. Therefore, coupling between nanoparticles also increases the thermal conductivity of nanofluids by creating a chain of nanoparticles connected to each other that causes the heat transfer to occur at a higher rate.

The advantages of nanofluids and the development of nanotechnology have led to use of nanofluids in the boiling process, in many recent empirical studies. In the cooling of some industrial systems, heat transfer may occur in all regions of the boiling curve and cover a wide range of heat
fluxes. For this reason, researchers have studied the two nucleate and film boiling regimes. Although these two boiling regimes have been studied numerically by some researchers [2-5], but in many studies, they have been studied experimentally as well, which is reviewed as follows:

Shahmoradi et al. [6] conducted the pool boiling experiments of water-alumina nanofluid with volumetric concentrations of less than 0.1% on a flat plate of copper. It was observed that by increasing the volumetric concentration from 0.01% to 0.1% the heat transfer coefficient of nucleate boiling decreases and the critical heat flux (CHF) increases. The decrease of heat transfer coefficient of the nucleate boiling is due to the deposition of nanoparticles during the boiling process and the filling of the nucleation sites and the increase of heat flux is due to the increase in surface wettability. Raveshi et al. [7] investigated the nanofluid pool boiling of a binary mixture of water-ethylene glycol with alumina at the same volume ratio on a flat plate of copper. It was found that there is an optimum volumetric concentration for nanofluids, which has the highest nucleate boiling heat transfer coefficient. The optimum concentration was 0.75% and the highest increase of nucleate boiling heat transfer coefficient is reported 64% compared to base fluid.

Umesh and Raja [8] investigated the pool boiling of pentane-copper oxide nanofluid with volumetric concentrations of 0.005% and 0.01% on flat heaters of brass. It was observed that at low volumetric concentrations, the nucleate boiling heat transfer coefficient increased by 5% to 25% compared to the base fluid but decreased with increasing nanofluid volumetric concentration. Ji et al. [9] conducted the boiling experiments of water-silica nanofluid with mass concentrations of 0.025%, 0.05%, and 0.1%, to investigate the effects of surface wettability on pool boiling. The results showed that by increasing the mass concentration from 0.025% to 0.1%, the nucleate boiling heat transfer coefficient decreased. The reason for this decrease was the deposition of nanoparticles on the boiling surface, which made the surface more hydrophilic and delayed the occurrence of nucleate boiling. Dareh et al. [10] conducted pool boiling experiments of pure water and water-alumina nanofluids with 0.0025%, 0.005%, and 0.01% volumetric concentrations on the micro
and nano-structured surfaces. The results showed that for all the surfaces, the CHF of the nanofluid was higher than the base fluid.

Kiyomura et al. [11] investigated the pool boiling of a Fe₂O₃ water-based nanofluid at mass concentrations of 0.029 and 0.29 gr/lit on copper surface. The effects of nanoparticles deposition and surface roughness on contact angle, surface wettability and heat transfer coefficient of nucleate boiling were investigated. The results showed that the highest nucleate boiling heat transfer coefficient was for polished surface with lower concentration of nanoparticles. Vasudevan et al. [12] investigated the pool boiling of reduced graphene oxide water-based nanofluid with volumetric concentrations of 0.2%, 0.6%, and 0.8% on a flat plate of copper. The results showed that by increasing the volumetric concentration from 0.2% to 0.8%, the CHF increases. It was observed that the increase of CHF is due to the increase in bubble density and existence of small bubbles. Reddy and Venkatachalapathy [13] investigated the pool boiling of hybrid nanofluid (Al₂O₃-CuO/water) with various volumetric concentrations on a flat plate of copper. The results showed that the CHF of the hybrid nanofluid was higher than the single type nanofluid. It was observed that by increasing the volumetric concentration from 0.01% to 0.1%, the nucleate boiling curves shifted towards right due to nanoparticle deposition leading to enhanced capillary action.

Kamel and Lezsovits [14] conducted the pool boiling experiments of tungsten oxide water-based nanofluid with volumetric concentrations of 0.005%, 0.01%, and 0.05% on horizontal copper tube. It was observed that by increasing the applied heat flux, the nucleate boiling heat transfer coefficient increases. The results showed that by increasing the volumetric concentration from 0.005% to 0.05%, the nucleate boiling heat transfer coefficient decreases. Mohammadi and Khayat [15] conducted the pool boiling experiments of Al₂O₃ and CuO water-based nanofluids with 0.1% volumetric concentration on a flat plate of copper. The results showed that the CHF of the nanofluids was higher than the water. It was observed that the boiling of nanofluids on the
micro-groove surface cannot be used for a long time process because of deposition of nanoparticles over the time and creation of insulation layer on the surface.

Gylys et al. [16] presented experimental results of film boiling by testing the cooling process of spherical surfaces in subcooled water. Spherical surfaces are made of three different types of steel, copper and aluminum. The results showed that the minimum film boiling temperature was influenced by the thermal diffusion characteristics of the surface (thermal conductivity, thermal capacity and density), water temperature and heat transfer rate between the surface and the liquid. Arai and Furuya [17] investigated the film boiling experiments by quenching a high-temperature stainless steel sphere in Al₂O₃ water-based nanofluid at 0.024% to 1.3% volumetric concentrations. The film boiling heat transfer rate of nanofluid is reported to be approximately similar or slightly lower than water. Ciloglu et al. [18] investigated the pool-film boiling of Al₂O₃, SiO₂, TiO₂ and CuO water-based nanofluids with 0.1% volumetric concentration. A high temperature cylindrical rod was used as the boiling surface. The results showed that during the repetitive tests, the cooling time was reduced and the main reason was to change the surface properties due to the deposition of the nanoparticles on the surface.

Li et al. [19] conducted boiling experiments by quenching hot stainless steel spheres in the water-based nanofluid pool in the presence of carbon nanotubes (CNTs) of various sizes. The results showed that due to differences in the size of the nanoparticles, the CHF and Leidenfrost point increased up to different values. The results of the contact angle and roughness test showed that the porous layers influence surface roughness rather than surface wettability. Kang et al. [20] conducted film boiling experiments to evaluate the effects of surface hydrophobicity on minimum film boiling temperature and minimum heat flux (MHF) by quenching spherical surfaces in saturated water. Superhydrophobic surfaces are prepared by anodic oxidation on zirconium surface. The results showed that the superhydrophobic surfaces increase the minimum film boiling temperature and the MHF.
Wcis’lik [21] reviewed the effect of adding common nanoparticles to the base fluid on the Leidenfrost temperature and presented a simple economic analysis of the use of nanoparticles. Among five nanoparticles investigated in this paper (Ag, Al₂O₃, SiO₂, TiO₂ and C-diamond), Al₂O₃ nanoparticles with a size of 39 nm and volumetric concentration of 0.1% had the best thermal effect. In most of the analyzed cases, the minimum film boiling temperature is inversely correlated with the volumetric concentration of nanofluids. Talari et al. [22] investigated the effects of micro/nanostructured surfaces on the Leidenfrost drop temperature with an emphasis on its enhancement and discussed the mechanism of surface topology improvement. It was observed that multiscale surfaces, by combining the benefits of both nano and micro structures, significantly increase the Leidenfrost temperature and has a better performance.

The literature review appeared that nanofluids film boiling experiments have been performed on spherical and cylindrical surfaces, and not on the horizontal flat plate. The occurrence of film boiling at high temperatures has limited its experimental study so that the majority of boiling studies have focused on nucleate boiling. Due to the abilities of our instrument for working in high temperatures, in the present paper, it became possible to evaluate of film boiling experiments on the horizontal flat plate. The experimental study of nanofluids film boiling on the horizontal flat plate is a new aspect of the present paper. However, to conduct more comprehensive research, nucleate boiling is also investigated. For this purpose, the effects of adding nanoparticles to the base fluid on the nucleate and film boiling heat transfer coefficient, CHF, MHF, and minimum film boiling temperature are investigated experimentally.

2. Experimental apparatus and test procedure

2.1. Description of problem

In the present study, boiling experiments were carried out under the same laboratory conditions at ambient pressure of 80 kPa, ambient temperature of 23 °C and water boiling temperature of 92.9 °C. Boiling experiments were performed on a circular and polished copper surface with a
diameter of 25 mm. The fluids used for boiling experiments are pure deionized water and two types of \( \text{Al}_2\text{O}_3 (\alpha) \) and \( \text{SiO}_2 \) deionized water-based nanofluids. To investigate the effects of nanofluid volumetric concentration on the heat transfer characteristics of film and nucleate boiling, experiments were carried out with three volumetric concentrations of 0.1%, 0.3% and 0.5%.

2.2. Pool boiling experimental apparatus

The schematic of the pool boiling apparatus used in this study is shown in Figure 1. This device includes of a structural part, retaining bases and a test chamber. Data processing, lighting, power transmission and heating parts are located in the lower section of the test chamber. The test chamber is a Pyrex glass with a diameter, height and thickness of 200, 300 and 5 mm, respectively. In addition, to prevent heat dissipation, the outer part of Pyrex is coated with one layer of fiberglass, two layers of thermal insulation and one layer of aluminum insulation glue. On the top of the Pyrex, there is a safety glass cover with dimensions of 400×400 mm, and in this cover a pressure gauge and a safety valve are located. A pressure gauge was used to display the pressure inside the test chamber and to ensure it remained constant. The M-shaped rod pre-heater with a power of 500 W is located into the fluid to warm the operating fluid to its saturation temperature at atmospheric pressure before and during the test. A condenser with a diameter of 10 mm and a length of 15 cm was used to cool and condense the water into the chamber and a pump with a discharge of 400 lit/hr was used to keep the water inside the condenser continuously rotating.

The cartridge is a cylinder with two different cross-sections at top and base and is made of copper with a purity of 99%. Figures 2 (a) and (b) show the copper cartridge before being placed in the pool boiling apparatus. The total height of the cartridge is 120 mm and the upper and lower section diameters are 25 mm and 140 mm, respectively. The upper cross-section is used as the boiling surface. On the upper neck of this cartridge, three holes are created with a diameter of 2 mm and a distance of 7 mm from each other and the thermocouples are located on them. In the bottom part of the cartridge cross-section, eight holes with a diameter of 10 mm and a depth of 55 mm have
been created, which is the location of the heaters. In the present apparatus, a 3000 W variac with a variable output from 0 to 250 V is used to power the device.

To record the temperatures of the three thermocouples connected to the cartridge and a thermocouple inside working fluid, a TM4 type thermostat was used to record the data to the computer every second. Silicon paste has been used to prevent heat dissipation in holes where heaters and thermocouples are located in cartridges. In addition, silicon glues with a high thermal resistance have been used to seal Pyrex and its underlying steel, as well as between the cartridge and Teflon thermal insulation (PTFE). Teflon thermal insulation is a circle with the diameter of 14 cm and thickness of 3 cm. Figure 2 (c) shows how the PTFE wrapped around the copper cartridge. On the wall of this piece, three holes with a diameter of 3 mm were created to pass the thermocouples and aligned with the location of the thermocouples on the cartridge. The thermocouples used in this device are K type and covers a temperature range of -200 °C to 1350 °C.

To simplify the experiment procedure, the heat transfer in the cartridge is assumed to be one-dimensional, so it is necessary to insulate the cartridge to prevent heat loss in the radial direction. So first, the cartridge is covered by glass wool with a thermal conductivity of 0.04 W/m.°C and a temperature resistance of 750 °C. Then a layer of thick PTFE sheet is fastened to the glass wool. Then, another layer of glass wool and an elastomeric insulator are placed over the whole set and tightly closed.

2.3. Preparation of nanofluids

The nanofluids used in the boiling experiments of the present study include Al₂O₃ (α) and SiO₂ nanoparticles in deionized water-based fluid. In Table 1, the characteristics of the nanoparticles used in this study are presented.

To reach the volumetric concentrations of 0.1%, 0.3%, and 0.5% in a liter of deionized water, the required mass of each nanoparticle was calculated using Eq. (1). Table 2 shows the mass requirements of the nanoparticles for different volumetric concentrations.
\[ m = \frac{\rho_{np} \times V_{nf} \times (\varphi \times 10^{-2})}{(1 - \varphi \times 10^{-2})} \] (1)

In Eq. (1), \( \rho_{np} \) is the nanoparticle density, \( V_{nf} \) is nanofluid volume and \( \varphi \) is volumetric concentration.

Figure 3 shows a schematic of the nanofluid preparation process which is used in boiling experiments. For preparation the nanofluids, a magnetic stirrer was used to distribute the particles into the base fluid. Also, an ultrasonic probe (UP400St, hielscher) with the power of 400 W and a frequency of 24 kHz was used to stabilize the solution and an ultrasonic bath tank (WUC-D10H, DAIHAN Scientific Co., Ltd) with the power of 665 W and a frequency of 40 kHz was used to homogenize and remove the agglomerates.

To test the stability of nanofluids, the deposition of nanoparticles in the base fluid over time has been studied visually. For example, nanofluid stability test with 0.5% volumetric concentration is shown in Figures 4 (a) and (b). According to these figures, the deionized water-based \( \text{Al}_2\text{O}_3 \) and \( \text{SiO}_2 \) nanoparticles showed good stability after 21 days. It is noteworthy that the boiling experiments were performed one day after the nanofluids preparation.

To investigate the size and shape of nanoparticles, transmission electron microscopy (TEM) images of nanofluids were prepared. In Figures 5 (a) and (b), the TEM images of \( \text{Al}_2\text{O}_3 \) and \( \text{SiO}_2 \) nanoparticles in deionized water-based fluid with a volumetric concentration of 0.5% are shown, respectively. According to these figures, the nanoparticles are well dispersed in the base fluid and the dimensions reported in the images are consistent with the stated dimensions.

2.4. Measurement and data error analysis

First, the Pyrex chamber is filled with one liter of working fluid and the pre-heater is turn on to warm up the water to the saturated temperature (92.9 °C at 80 kPa). At this point, the condenser is turned on so that the vapors condense and return to the boiling chamber. In the next step, the main heaters are switched on to apply heat flux to the surface and the fluid. For this purpose, the voltage of the power supply is increased step by step until the boiling process reaches the CHF. After each
step of increasing voltage and reaching steady state, the temperature of the thermocouples is recorded by TM4 type thermostat to predict surface temperature and heat flux. In the present study, the steady state (temperature change of thermocouples less than 0.1 °C) achieved less than 15 minute in all experiments. After reaching the CHF, due to the lack of contact of the cooling fluid with the boiling surface, a sudden jump is observed at temperatures recorded by the thermocouples and the turbulence of the fluid under boiling process is reduced. An unstable vapor layer covers the surface and the boiling occurs transiently. In this step, although the operating voltage does not increase, the temperature of the thermocouples continues to increase. In order to observe and evaluate the stable film boiling, the surface temperature must be sufficiently high. Therefore, the boiling process after CHF is allowed to reach the highest thermocouple temperature of about 400 °C. Then, the applied voltage decreases to reduce the temperature rise of the thermocouples. In this step, with trial and error (decreasing and increasing voltage), the operating voltage is changed to keep the thermocouples temperature almost constant. In the next step, the temperature of the thermocouples must remain high so that the boiling process is stable in the film boiling region (point A in Figure 6). After reaching steady state, the applied voltage is reduced in a stepwise manner until the film boiling process reaches the MHF and the hysteresis curve of the film boiling can be plotted according to the schematic diagram of Figure 6 [23].

Figure 7 schematically shows the location of the thermocouples in the copper cartridge. As shown in Figure 7, \( T_1 \), \( T_2 \), and \( T_3 \) represent the thermocouple temperatures of 1, 2 and 3, respectively, and \( T_s \) represents the surface temperature.

With proper insulation around the copper cartridge, radial heat transfer to the environment can be neglected and heat transfer is considered as one dimensional along the cartridge. Therefore, with respect to the thermal conductivity of copper, the temperature of the thermocouples and the distance between the holes embedded in the cartridge, the heat flux can be calculated from Eq. (2).

\[
q'' = -k \frac{T_3 - T_1}{\Delta Z_{1-3}}
\]  

(2)
In Eq. (2), $\Delta Z_{1-3}$ is the distance between the thermocouples 1 and 3.

If the heat flux is known, the Fourier law can be used to predict the surface temperature at any constant heat flux according to Eq. (3).

$$T_s = T_1 - \frac{q'' \Delta Z_{s-1}}{k}$$  \hspace{1cm} (3)

In Eq. (3), $\Delta Z_{s-1}$ is the distance between the boiling surface and the thermocouple 1. The boiling heat transfer coefficient can also be calculated from Eq. (4).

$$h = \frac{q''}{(T_s - T_{sat})}$$  \hspace{1cm} (4)

The temperature change diagram of the three thermocouples, in four different fluxes, according to their position on the cartridge in the nucleate and film boiling regimes are plotted in Figures 8 and 9, respectively, to ensure one-dimensional heat transfer assumption. According to these figures, by least squares method, the deviation for nucleate boiling is greater than 0.99 and for film boiling is greater than 0.98. So one-dimensional heat transfer is assumed correct, but there is always some loss in a part of the heat generated in the elements.

Table 3 presents the uncertainty of the data of the present research experiments. It is necessary to explain that the holes of the thermocouples location in the copper block were produced by CNC numerical control machining.

The assumption that the thermal conductivity of copper remains constant during the test may cause error in the test results and therefore its uncertainty needs to be calculated. The thermal conductivity of copper at 100 °C and 300 °C are 395.89 W/m.°C and 382.89 W/m.°C, respectively [24]. In nucleate boiling experiments, the thermal conductivity of copper is considered constant and its uncertainty is 3.28%. Because of the large surface temperature variations in the film boiling experiments, the thermal conductivity variations of copper are not negligible and its value for each temperature is interpolated from the reference tables [24] and its maximum uncertainty is 0.063%.
In the present study, Moffat method [25] was used to calculate heat flux, surface and fluid temperature difference and boiling heat transfer coefficient uncertainties.

As shown by the Fourier heat conduction relation, the magnitude of the heat flux error depends on the thermal conductivity errors of the copper, temperatures and location of the thermocouples according to Eq. (5). Therefore, the heat flux uncertainty can be calculated from Eq. (6) by using Moffat method.

\[ q^* = f(k, \Delta T, \Delta Z) \]  
\[ \frac{U_{q^*}}{q^*} = \sqrt{\left( \frac{U_{T_1 - T_1}}{T_3 - T_1} \right)^2 + \left( \frac{U_{Z_1 - Z_1}}{Z_3 - Z_1} \right)^2 + \left( \frac{U_k}{k} \right)^2} \]  

The Eq. (7) can be used to calculate the uncertainty of the surface and fluid temperature difference (\( \Delta T_s \)).

\[ \frac{U_{\Delta T_s}}{\Delta T_s} = \sqrt{\left( \frac{U_{T_1 - T_{sat}}}{T_1 - T_{sat}} \right)^2 + \left( \frac{U_{Z_1}}{Z_1} \right)^2 + \left( \frac{U_k}{k} \right)^2} \]  

The Eq. (8) can be used to calculate the uncertainty of the boiling heat transfer coefficient.

\[ \frac{U_h}{h} = \sqrt{\left( \frac{U_{q^*}}{q^*} \right)^2 + \left( \frac{U_{\Delta T_s}}{\Delta T_s} \right)^2} \]  

Table 4 presents the heat flux, the surface and fluid temperature differences and the boiling heat transfer coefficient uncertainties. Based on the accuracy of the measuring instruments, the maximum error in the calculation of the heat flux and the heat transfer coefficient of the nucleate boiling were 8.6% and 9.7%, respectively, and in the calculation of the heat flux and the heat transfer coefficient of the film boiling were 11.7% and 11.9%, respectively.

3. Validation of results

In the present study, laboratory data were validated for both nucleate and film boiling regimes. For this purpose, the nucleate boiling data obtained from the experiments are compared with the empirical
relationships and the results of other researchers. In addition, the film boiling data obtained from the experiments are compared with valid experimental relationships. Finally, a repeatability test was performed to complete the verification.

Before conducting the experiments, the copper surface was polished by 1500 grain sanding to created smooth boiling surface. After surface preparation, experiments were performed using deionized water as the working fluid on the polished surface.

In Figure 10, the heat flux diagram is plotted versus the wall superheat temperature difference using the data of the deionized water boiling experiment on the polished copper surface.

Using the Rohsenow empirical relation [26], the heat flux of a nucleate boiling can be calculated in terms of the wall superheat temperature difference according to the Eq. (9).

$$\left[ \frac{c_{pl} \Delta T_{sb}}{i_{lv}} \right] = C_{sf} \left[ \frac{q^*}{\mu i_{lv}} \sqrt{\frac{\sigma}{g (\rho_l - \rho_v)}} \right]^{m+1} \frac{c_p \mu}{k}$$

(9)

In Eq. (9), $c_{pl}$, $\mu$, $k$ and $\rho_l$ are the specific heat capacity, dynamic viscosity, thermal conductivity and liquid density, respectively and $\rho_v$ is the vapor density, $i_{lv}$ is latent heat of evaporation and $\sigma$ is surface tension. For boiling of the water, $n = 0.33$, $m = 0$, and surface-fluid correction coefficients for water-Cu composition is $C_{sf} = 0.013$. Using the Zuber empirical relation [27], the CHF for pure deionized water can be calculated according to Eq. (10).

$$q_{v, \text{max}}^* = 0.13 i_{lv} \rho_v 0.5 \left[ \sigma g (\rho_l - \rho_v) \right]^{0.25}$$

(10)

In Figure 11, the nucleate boiling curve of the present study is compared with the Rohsenow empirical relation, which has a maximum error of 9.7%. As shown in Figure 11, the Rohsenow relation agrees satisfactorily with the data of the present experiments. Using the Zuber empirical relation, the CHF for pure deionized water is 1108 kW/m$^2$, which has 7.9% error compared to the CHF in the present study.
In Figure 12, the nucleate boiling curve of the present study is compared with the results of other researchers [6,28,29]. As shown in Figure 12, the data of the present experiments have a good agreement with other empirical data.

Berenson [30] by combining the theory of wave hydrodynamic instability with Bromley's model [31], has proposed an experimental relation for film boiling on a horizontal flat plate. By using it the heat transfer coefficient of the film boiling \( (h_{fb}) \) can be calculated in terms of the wall superheat temperature difference \( (\Delta T_{sat}) \) according to the Eq. (11).

\[
h_{fb} = 0.425 \left[ \frac{k_v \rho \Delta g i'_{lv}}{\mu \Delta T_{sat} \sqrt{\sigma / g (\Delta \rho)}} \right]^{0.425}
\]  

(11)

In Eq. (11), \( i'_{lv} \) is the effective latent heat of evaporation, which can be calculated from Eq. (12).

\[
i'_{lv} = i_{lv} \left[ 1 + 0.5 \left( \frac{c_{pv} \Delta T_{sat}}{i_{lv}} \right) \right]
\]  

(12)

Using the Berenson empirical relations, the MHF and the wall superheat temperature difference of the film boiling starting point \( (\Delta T_{min}) \) can be calculated. Because the steam properties are implicitly dependent to temperature, the iteration method is used.

\[
q_{min}^* = 0.091 \rho_i i'_{lv} \left[ \frac{\sigma g \Delta \rho}{(\rho_i + \rho_s)^2} \right]^{0.425}
\]  

(13)

\[
\Delta T_{min} = \frac{q_{min}^*}{h_{fb}}
\]  

(14)

Henry [32] has proposed Eq. (15) by considering the effects of solid surface thermophysical properties on the minimum film boiling temperature.

\[
\frac{T_{min}^* - T_{min}}{T_{min}^* - T_1} = 0.42 \left[ \frac{(\rho c k)_i}{(\rho c k)_w C_w (T_{min}^* - T_{sat})} \right]^{0.6}
\]  

(15)

In Eq. (15), \( T_{min}^* \) is the minimum film boiling temperature, which is obtained by the Berenson relation. The index \( f \) is for saturated liquid and \( w \) is for solid surface.
In Figure 13, the film boiling heat transfer coefficient of the present study is compared with the Berenson empirical relation, which has a maximum error of 10.7%.

By using Berenson empirical relations, $\Delta T_{\text{min}}$ is obtained 77.02 °C for pure deionized water. By using the Henry relation and considering the effects of the thermophysical properties of copper, $\Delta T_{\text{min}}$ is obtained 146 °C. In the present study, $\Delta T_{\text{min}}$ for pure deionized water on a polished cooper surface is obtained 159.7 °C, which differs 9.3% from the Henry empirical relation.

In order to investigate the repeatability test, pure deionized water boiling experiments were performed on the polished copper surface on two different days and the nucleate and film boiling diagrams are plotted in Figure 14. The amount of error in the CHF is 1.9% and in the MHF is 2.8%, which indicates the accuracy of the results.

Figure 15 shows how bubbles are formed on the polished copper surface at different heat fluxes. At low heat fluxes (Figure 15 (a)), the bubbles are smaller and as the heat flux increases, the small bubbles merge to form larger bubbles (Figure 15 (b) to (f)). After CHF and the transient boiling region, a layer of stable steam coated the surface and the film boiling is occurred (Figure 15 (h)).

4. Results

4.1. Nucleate boiling results

In the present experiments, the CHF value of pure deionized water is 1196.43 kW/m², which occurs at a wall superheat temperature difference of 20.89 °C. In addition, maximum nucleate boiling heat transfer coefficient of pure deionized water is 57.27 kW/m²°C.

In Figure 16, the Al₂O₃ and SiO₂ deionized water-based nanofluids with three volumetric concentrations of 0.1%, 0.3% and 0.5% and pure deionized water nucleate boiling curve is plotted. As shown in Figure 16, the CHF of Al₂O₃ nanofluid occurs at higher wall superheat temperature difference than pure deionized water such that $\Delta T_{\text{sat}}$ for volumetric concentrations of 0.1%, 0.3% and
0.5%, is 57.4 °C, 62.1 °C and 63.8 °C, respectively. The presence of Al₂O₃ nanoparticles in the de-ionized water-based nanofluid, increases the CHF so that its values for volumetric concentrations of 0.1%, 0.3% and 0.5% are 1410 kW/m², 1600.5 kW/m² and 1729.6 kW/m², respectively. Figure 16 also indicates that the presence of SiO₂ nanoparticles in the deionized water-based nanofluid, has delayed the integration of the bubbles into each other and significantly increased the wall superheat temperature difference in which the CHF occurring. So that the CHF for volumetric concentrations of 0.1%, 0.3% and 0.5% are in wall superheat temperature difference of 44 °C, 47.1 °C and 52.7 °C, respectively. The CHF values for SiO₂ nanofluid with volumetric concentrations of 0.1%, 0.3% and 0.5% are 1550.42 kW/m², 1660.35 kW/m² and 1701.27 kW/m², respectively.

In Figure 17, the nucleate boiling heat transfer coefficient of Al₂O₃ and SiO₂ deionized water-based nanofluids with three volumetric concentrations of 0.1%, 0.3% and 0.5% is plotted versus the heat flux. As shown in Figure 17, at a constant heat flux, the nucleate boiling heat transfer coefficient of the Al₂O₃ and SiO₂ nanofluids is reduced compared to pure deionized water. At higher heat fluxes, there is a further reduction, which is due to the deposition of the nanoparticles on the boiling surface. As the volumetric concentration of Al₂O₃ nanofluid increases from 0.1% to 0.5%, the heat transfer coefficient of the nucleate boiling increases. Maximum nucleate boiling heat transfer coefficient of Al₂O₃ deionized water-based nanofluid for volumetric concentrations of 0.1%, 0.3% and 0.5% is 27.30 kW/m².°C, 32.10 kW/m².°C and 38.26 kW/m².°C, respectively. Unlike Al₂O₃ nanofluid, the nucleate boiling heat transfer coefficient of SiO₂ deionized water-based nanofluid decreases with increasing volumetric concentration from 0.1% to 0.5%. Maximum nucleate boiling heat transfer coefficient of SiO₂ deionized water-based nanofluid for volumetric concentrations of 0.1%, 0.3% and 0.5% is 52.15 kW/m².°C, 49.83 kW/m².°C and 44.53 kW/m².°C, respectively.

In this section, the results of the nucleate boiling of the nanofluids with three different volumetric concentrations on the polished copper surface are summarized and compared with the
results of pure deionized water. The results showed that for both nanofluids and all volumetric concentrations, the CHF occurs at a higher wall superheat temperature difference than that of pure deionized water. In addition, in all cases, the presence of nanoparticles in the base fluid improves the CHF. The boiling of $\text{Al}_2\text{O}_3$ deionized water-based nanofluid with 0.5% volumetric concentration had the highest CHF, with an increase of 44.56% compared to pure deionized water. The $\text{SiO}_2$ deionized water-based nanofluid with 0.5% volumetric concentration also had the best performance compared to two other concentrations so that the CHF value increases 42.19% compared to pure deionized water.

In nanofluid boiling, there are two phenomena of increased heat transfer due to increased thermal conductivity, convection and fluid turbulence, and reduced heat transfer due to closure of surface holes by nanoparticles and reduced number of nucleation sites. The results of the present study show that in nucleate boiling, the increasing effect of heat transfer is dominated by its decreasing effect and for both nanoparticles in all volumetric concentrations, the heat transfer coefficient of nucleate boiling is decreased compared to pure deionized water. The value of this reduction was greater for the $\text{Al}_2\text{O}_3$ nanofluid compared to the $\text{SiO}_2$ nanofluid because the size of the $\text{Al}_2\text{O}_3$ nanoparticles was larger and their deposition on the boiling surface was greater.

4.2. Film boiling results

In the present experiments, the MHF value of pure deionized water is 36.48 kW/m$^2$, which occurs at a wall superheat temperature difference of 159.7 °C. In addition, maximum film boiling heat transfer coefficient of pure deionized water is 0.228 kW/m$^2$.°C.

In Figure 18, the $\text{Al}_2\text{O}_3$ and $\text{SiO}_2$ deionized water-based nanofluids with three volumetric concentrations of 0.1%, 0.3% and 0.5% and pure deionized water film boiling curve is plotted. As shown in Figure 18, the presence of $\text{Al}_2\text{O}_3$ nanoparticles in the base fluid caused the starting point of stable film boiling to be at higher wall superheat temperature difference such that $\Delta T_{\text{min}}$ for volumetric concentrations of 0.1%, 0.3% and 0.5%, is 176.3 °C, 172.5 °C and 170.7 °C,
respectively. By increasing the volumetric concentration of Al$_2$O$_3$ nanofluid from 0.1% to 0.5%, stable film boiling has started at lower wall superheat temperature difference. The MHF values for Al$_2$O$_3$ nanofluid with volumetric concentrations of 0.1%, 0.3% and 0.5% are 44.92 kW/m$^2$, 47.09 kW/m$^2$ and 49.25 kW/m$^2$, respectively, which increased compared to pure deionized water. Similar to Al$_2$O$_3$ nanoparticles, the presence of SiO$_2$ nanoparticles in the base fluid caused the starting point of stable film boiling to be at higher wall superheat temperature difference such that $\Delta T_{\text{min}}$ for volumetric concentrations of 0.1%, 0.3% and 0.5%, is 172.4 °C, 177.4 °C and 179.9 °C, respectively. Unlike Al$_2$O$_3$ nanofluid, in SiO$_2$ nanofluid with increasing volumetric concentration from 0.1% to 0.5%, stable film boiling has begun at higher wall superheat temperature differences. The MHF values for SiO$_2$ nanofluid with volumetric concentrations of 0.1%, 0.3% and 0.5% are 42.81 kW/m$^2$, 47.05 kW/m$^2$ and 49.03 kW/m$^2$, respectively, which increased compared to pure deionized water.

In Figure 19, the film boiling heat transfer coefficient of Al$_2$O$_3$ and SiO$_2$ deionized water-based nanofluids with three volumetric concentrations of 0.1%, 0.3% and 0.5% is plotted versus wall superheat temperature difference. According to Figure 19, for Al$_2$O$_3$ nanofluid in all three volumetric concentrations, the film boiling heat transfer coefficient at a constant wall superheat temperature difference increased compared to pure deionized water. The value of this increment is more evident at the lower wall superheat temperature differences. Maximum film boiling heat transfer coefficient of Al$_2$O$_3$ deionized water-based nanofluid for volumetric concentrations of 0.1%, 0.3% and 0.5% is 0.255 kW/m$^2$.°C, 0.273 kW/m$^2$.°C and 0.288 kW/m$^2$.°C, respectively. Figure 19 also indicates that the presence of SiO$_2$ nanoparticles improves the heat transfer coefficient of the film boiling compared to pure deionized water. However, similar to the Al$_2$O$_3$ nanoparticles with increasing in wall superheat temperature difference, the positive effects of the presence of SiO$_2$ nanoparticles on the heat transfer coefficient of film boiling has decreased. Maximum film boiling heat transfer coefficient of SiO$_2$ deionized water-based nanofluid for
volumetric concentrations of 0.1%, 0.3% and 0.5% is 0.248 kW/m².°C, 0.265 kW/m².°C and 0.275 kW/m².°C, respectively.

In this section, the results of the film boiling of the nanofluids with three different volumetric concentrations on the polished copper surface are summarized and compared with the results of pure deionized water. The results showed that for both nanofluids and all volumetric concentrations, stable film boiling is started at higher wall superheat temperature difference compared to pure deionized water, due to the change in surface hydrophilicity induced by the nanoparticle deposition during boiling. Among the experiments in the present study, the highest MHF was related to Al₂O₃ deionized water-based nanofluid with a volumetric concentration of 0.5%, with an increase of 35.01% compared to pure deionized water. In SiO₂ deionized water-based nanofluid, the volumetric concentration of 0.5% had the best performance compared to two other concentrations and the MHF increased 34.40% compared to pure deionized water. For both nanofluids, the film boiling heat transfer coefficient is increased compared to pure deionized water.

Droplet test was performed to investigate the change of surface hydrophilicity after the boiling of nanofluids. In Figure 20, the contact angle of the water droplet and the surface before the boiling and after the boiling of the nanofluids is shown. Droplet test revealed that the nanoparticle deposition on the boiling surface made the boiling surface more hydrophilic. According to Figure 20, the contact angle of the water droplet and the surface before boiling is 83°. After the nanofluid boiling and the nanoparticle deposition on the surface, the contact angle of the water droplet and the surface decreased sharply so that the values for the deposited surfaces by the Al₂O₃ and SiO₂ nanoparticles were 25° and 28°, respectively. As the surface becomes more hydrophilic, the droplet spreads rapidly to the surface, thereby the nucleation sites are fill and inactive by fluid and reducing the heat transfer coefficient of nucleate boiling. The more hydrophilic the surface, the greater the size and the time of bubble growth, resulting in a lower bubble separation frequency, thus delaying the occurrence of critical heat flux and minimum heat flux. In film boiling, the surface temperature is so
high that a stable vapor layer forms on the boiling surface which causes to be no contact between liquid and solid. Thus, heat transfer is accomplished mainly by conduction and convection through the vapor film. Lack of direct solid-liquid contact prevents nucleation sites from being filled and inactivated by liquid droplets. In other words, in film boiling, surface hydrophilicity has no significant effect on filling the nucleation sites and destroying the bubbling process. For this reason, the factor of improving the thermal properties of nanofluids overcomes the destructive factor of inactivation of nucleation sites, thus the heat transfer coefficient of film boiling increases.

5. Conclusion

In this paper, the nucleate and film boiling heat transfer characteristics of Al₂O₃ and SiO₂ deionized water-based nanofluids have been studied experimentally. For this purpose, nanofluids were prepared with three volumetric concentrations of 0.1%, 0.3% and 0.5% and experiments were performed using pool boiling apparatus. It is noteworthy that the new results of nanofluids film boiling on the horizontal flat plate have been presented.

The nucleate boiling results showed that addition of Al₂O₃ and SiO₂ nanoparticles to the base fluid reduces the heat transfer coefficient of the nucleate boiling. From this perspective, the addition of nanoparticles has led to a poor performance of nucleate boiling compared to pure deionized water. On the other hand, the CHF of nanofluids in all three volumetric concentrations of 0.1%, 0.3% and 0.5% was significantly higher than that of pure deionized water. For both Al₂O₃ and SiO₂ deionized water-based nanofluid, the CHF increased with increasing volumetric concentration. Therefore, from the perspective of the CHF, the addition of nanoparticles to the base fluid improves the performance of the boiling process.

The film boiling results showed that for both Al₂O₃ and SiO₂ deionized water-based nanofluid with three volumetric concentrations of 0.1%, 0.3% and 0.5% stable film boiling starts at higher wall superheat temperature difference than pure deionized water. In addition, for both Al₂O₃ and SiO₂
deionized water-based nanofluid, as the volumetric concentration increases, the MHF increases. Due to the increase of the MHF and the occurrence of film boiling at higher wall superheat temperature difference for the nanofluids (compared to the base fluid), it can be concluded that adding nanoparticles to the base fluid improves the film boiling performance. It is interesting that nanofluids improved the film boiling heat transfer coefficient. For both nanofluids, by increasing the volumetric concentration from 0.1% to 0.5% the heat transfer coefficient of film boiling increases.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>C</td>
<td>Constant coefficient</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat capacity (J/kg.°C)</td>
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<tr>
<td>g</td>
<td>Gravitational acceleration (m/s²)</td>
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<tr>
<td>$h$</td>
<td>Boiling heat transfer coefficient (W/m².°C)</td>
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<tr>
<td>$i$</td>
<td>Latent heat of evaporation (J/kg)</td>
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<tr>
<td>$k$</td>
<td>Thermal conductivity (W/m.°C)</td>
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<tr>
<td>$m$</td>
<td>Mass (kg)</td>
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<tr>
<td>$q''$</td>
<td>Heat flux (W/m²)</td>
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<tr>
<td>$T$</td>
<td>Temperature (°C)</td>
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<td>$U$</td>
<td>Uncertainty</td>
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<tr>
<td>$V$</td>
<td>Volume (m³)</td>
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<tr>
<td>$Z$</td>
<td>Thermocouples location in cartridge (m)</td>
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<tr>
<td>$\Delta T$</td>
<td>Wall superheat (°C)</td>
</tr>
<tr>
<td>$\mu$</td>
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<tr>
<td>$\rho$</td>
<td>Density (kg/m³)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Surface tension (N/m)</td>
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<tr>
<td>$\phi$</td>
<td>Volumetric concentration of nanofluid</td>
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Subscripts
f    Saturated liquid
fb   Film boiling
l    Liquid
max  Maximum
min  Minimum
nf   Nanofluid
np   Nano particle
s    Boiling surface
sat  Saturation
sf   Solid-Fluid
v    Vapor
w    Solid surface

Abbreviations
CHF  Critical heat flux (W/m²)
MHF  Minimum heat flux (W/m²)
PTFE Poly tetra fluoro ethylene
TEM  Transmission electron microscopy

References


**Figure captions**

**Figure 1.** Pool boiling apparatus and its components in schematic form.

**Figure 2.** (a) and (b) Copper cartridge before being placed in the pool boiling apparatus (c) PTFE wrapped around the copper cartridge.

**Figure 3.** Schematic of nanofluids preparation for boiling experiments.

**Figure 4.** Deposition test of deionized water-based nanoparticles at a volumetric concentration of 0.5% (a) Al₂O₃ (b) SiO₂.

**Figure 5.** TEM image of deionized water-based nanoparticles at a volumetric concentration of 0.5% (a) Al₂O₃ (b) SiO₂.

**Figure 6.** Schematic of the pool boiling curve [23].

**Figure 7.** Schematic of the location of the thermocouples in the copper cartridge.

**Figure 8.** Linear temperature variations of thermocouples depending on their location on the cartridge for nucleate boiling.

**Figure 9.** Linear temperature variations of thermocouples depending on their location on the cartridge for film boiling.

**Figure 10.** Heat flux curve versus wall superheat temperature difference for nucleate and film boiling of deionized water on polished copper surface.

**Figure 11.** Comparison of the nucleate boiling curve of the present study with the Rohsenow experimental relationship.

**Figure 12.** Comparison of the nucleate boiling curve of the present study with the results of other researchers.

**Figure 13.** Comparison of the film boiling heat transfer coefficient curve of the present study with the Berenson empirical relation.

**Figure 14.** Repeatability of pure deionized water nucleate and film boiling on polished copper surface.
Figure 15. Bubbles formation and vapor film on the polished copper surface.

Figure 16. Al$_2$O$_3$ and SiO$_2$ deionized water-based nanofluids nucleate boiling curve at different volumetric concentrations.

Figure 17. Nucleate boiling heat transfer coefficient versus heat flux for Al$_2$O$_3$ and SiO$_2$ deionized water-based nanofluids with different volumetric concentrations.

Figure 18. Al$_2$O$_3$ and SiO$_2$ deionized water-based nanofluids film boiling curve at different volumetric concentrations.

Figure 19. Film boiling heat transfer coefficient versus wall superheat temperature difference for Al$_2$O$_3$ and SiO$_2$ deionized water-based nanofluids with different volumetric concentrations.

Figure 20. The static contact angle of the water droplet on the surface (a) before boiling (b) after SiO$_2$ deionized water-based nanofluid boiling (c) after Al$_2$O$_3$ deionized water-based nanofluid boiling.

Table captions

Table 1. Specifications of nanoparticles.

Table 2. Required mass of nanoparticles in different volumetric concentrations.

Table 3. Experimental data uncertainty.

Table 4. Uncertainty of parameters in nucleate and film boiling.

![Figure 1.](image-url)
Figure 2.

Figure 3.
Figure 4.
Figure 5.

Figure 6.
Figure 10.

Figure 11.

Figure 12.
Figure 13.

Figure 14.

Figure 15.

(a) $q'' = 290.31 \text{ kW/m}^2$
(b) $q'' = 411.28 \text{ kW/m}^2$
(c) $q'' = 690.35 \text{ kW/m}^2$
(d) $q'' = 873.14 \text{ kW/m}^2$

(e) $q'' = 952.30 \text{ kW/m}^2$
(f) $q'' = 1121.01 \text{ kW/m}^2$
(g) Transient boiling
(h) $q'' = 58.78 \text{ kW/m}^2$
Figure 16.

Figure 17.

Figure 18.
Figure 19.

Figure 20.

Table 1.

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<th>Al₂O₃ (α)</th>
<th>SiO₂</th>
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<tr>
<td>Producer</td>
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<td>Degussa</td>
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<tr>
<td>Color</td>
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<td>Dimension (nm)</td>
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<td>Density (gr/cm³)</td>
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Table 2.

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<th>Al₂O₃ (α) (gr)</th>
<th>SiO₂ (gr)</th>
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<tr>
<td>Volumetric Concentration of 0.1%</td>
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<td>Volumetric Concentration of 0.3%</td>
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<td>Volumetric Concentration of 0.5%</td>
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Table 3.

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<td>Thermocouples temperature (°C)</td>
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<td>Voltage (V)</td>
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</tr>
<tr>
<td>Current (I)</td>
<td>± 0.1%</td>
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<td>CNC Machining (mm)</td>
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Table 4.

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<th>Uncertainty in film boiling (%)</th>
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<td>Surface and fluid temperature differences (°C)</td>
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<tr>
<td>Heat transfer coefficient (kW/m².°C)</td>
<td>± 9.7</td>
<td>± 11.9</td>
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</table>

Biographies

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