

Article

Experimental Investigation of Nucleate Pool Boiling Characteristics Using SiO₂ Nanofluids

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Abstract

Boiling is one of the most effective mechanisms for heat removal, enabling the dissipation of high heat fluxes at relatively low temperature differences. This makes it particularly useful in applications such as electronic cooling, power systems, and energy engineering. In this study, heat-transfer enhancement during the boiling of water and water-based silicon dioxide (SiO₂) nanofluids at concentrations ranging from 0.01 to 1 wt.% under atmospheric pressure was analyzed. The heat-transfer surfaces consisted of copper samples with a roughness of $Ra = 0.143 \mu\text{m}$. The aim of this study was to determine how the addition of SiO₂ nanoparticles to the working fluid influences heat flux and the heat-transfer coefficient under nucleate boiling conditions. The results demonstrated that the use of SiO₂/water nanofluids can modify the characteristics of the pool boiling process. The maximum achieved heat flux reached approximately 1704.2 kW m^{-2} , while the heat-transfer coefficient exceeded $55.4 \text{ kW m}^{-2}\text{K}^{-1}$. The obtained results confirm that the addition of silicon dioxide nanoparticles can significantly increase the critical heat flux in nucleate boiling systems, particularly in applications requiring intensive heat removal for cooling. The findings demonstrate that SiO₂ nanofluids hold significant potential for high-heat-flux applications, particularly in the thermal management of miniaturized electronic systems and advanced power engineering.

Keywords: nucleate boiling; nanofluids; silicon dioxide nanoparticles (SiO₂); heat transfer



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1. Introduction

Miniaturization of devices constitutes a major challenge for modern engineering. Its essence lies not only in reducing the size of equipment, but also in maintaining existing performance parameters, and often even improving them. This necessitates the design of increasingly advanced solutions that, despite limited space, ensure high performance, reliability, and energy efficiency. One of the key challenges is the effective cooling of such devices, due to the high-heat-flux densities involved. In such cases, air cooling alone proves to be insufficient. A very popular, cost-effective, and conceptually simple cooling method is pool boiling. In this process, heat is removed from the heat-transfer surface through the phase change of a liquid into vapor, enabling the transfer of significant amounts of thermal energy. Boiling occurs without forced liquid flow, eliminating the need for additional

equipment to ensure circulation. This allows for considerable space savings, which is particularly important in miniaturized devices.

Pool boiling is commonly characterized by parameters such as the heat-transfer coefficient (HTC) and the critical heat flux (CHF) [1]. Based on these, boiling curves are constructed, and their analysis enables comparison of the heat-transfer performance during boiling [2]. The heat-transfer coefficient provides information about the amount of heat removed per unit surface area for a given temperature difference between the surface and the cooling liquid. For water on a flat copper surface with a roughness Rq in the range of 0.05–0.25 nm, researchers have reported HTC values ranging from approximately 30 and 72 kW m⁻²K⁻¹. Therefore, the heat-transfer coefficient (HTC) determines the heat-transfer performance. In turn, the critical heat flux defines the maximum heat flux that can be dissipated from the surface. Exceeding this value leads to a boiling crisis. This is the point at which the system reaches the limit of its cooling capability due to the onset of film boiling. During this process, the heat-transfer surface becomes overheated as a result of the formation of a large number of vapor bubbles near the surface. These bubbles are not effectively removed, preventing fresh liquid from reaching the surface. Consequently, the vapor layer acts as a thermal insulator, reducing heat-transfer efficiency and potentially leading to undesirable effects in the system. According to the literature, the CHF value for water on a flat copper surface ($Rq = 0.05\text{--}0.25$ nm) ranges from approximately 772 to 1250 kW m⁻² [3]. Considering the above, it is crucial in pool boiling studies to determine both HTC and CHF in order to fully assess the performance limits of the applied heat exchanger and the cooling fluid. While the HTC reflects the efficiency of the heat-transfer process during normal operation, the CHF defines the safety limit of the system, beyond which a rapid increase in the heating surface temperature may occur, potentially leading to heater failure or damage.

The significant development of nanotechnology in recent years has contributed to a growing interest in the study of nanofluids and their application in heat-transfer processes. Nanoparticles with sizes ranging from 1 nm to 100 nm have proven to be much more advantageous compared to micro- and millimeter-sized particles, as they exhibit higher thermal conductivity and better suspension stability [4–6]. The addition of inorganic substances in the form of nanoparticles to a base fluid alters boiling characteristics not only by increasing the interaction surface between the fluid and the heat exchanger, but also by modifying the nucleation mechanism [7,8]. The resulting colloidal mixture, compared to the pure base fluid, exhibits enhanced thermal conductivity and altered wettability properties, which significantly affect heat-transfer performance [9]. For example, the thermal conductivity of water at 298 K is approximately 0.61 W m⁻¹K⁻¹, whereas for SiO₂ nanoparticles ($d = 65$ nm), it exceeds this value and reaches approximately 1.38 W m⁻¹K⁻¹ [10]. The selection of the base fluid itself primarily depends on the intended application. In boiling processes, water is most commonly used due to its high latent heat of vaporization, which enhances heat transfer. Additionally, its environmental neutrality, chemical stability, low cost, and wide availability make it a very practical choice. In cases where lower boiling temperatures are required, ethanol, oils, or fluorinated fluids such as Novec-649 and FC-72 are often employed [9,11]. A comparison of boiling curves for different fluids enables the appropriate selection of a working medium tailored to the specific requirements of a given process.

Nanofluids are primarily produced using two methods: one-step and two-step techniques. In the first approach, nanoparticles are synthesized directly within the base fluid. In contrast, in the second method, pre-prepared nanoparticles in powder form are dispersed into the base fluid. For large-scale production, the second method is generally preferred [12]. A common practice is the subsequent stabilization of the resulting colloidal suspension by

adjusting the pH, adding surfactants, or applying ultrasonic treatment to ensure proper particle dispersion [4,12–15]. During nanofluid preparation, particular attention is paid to the selection of nanoparticles added to the base fluid. Materials with high thermal conductivity are typically used, most commonly metals (e.g., copper, silver, gold), metal oxides (such as silica, titanium dioxide, and aluminum oxide), and carbon nanotubes [4,7,9]. In recent years, researchers have also considered the use of hybrid nanoparticles, expecting enhanced thermal conductivity due to the synergistic effects of combining two or more types of materials [6,16–18]. For effective heat transfer, the concentration of nanoparticles in the base fluid must remain within an optimal range. Too low a concentration does not lead to a noticeable improvement in thermophysical properties, whereas too high a concentration results in particle deposition on the heat-transfer surface, increased thermal resistance, and deterioration of boiling performance [5,14]. In the study by Mukherjee et al. [19], the influence of silica nanoparticle concentration in water on thermal performance during pool boiling was investigated. Stable nanofluids with concentrations ranging from 0.0001 to 0.1 vol.% were prepared. The results showed that the greatest enhancement was achieved at a concentration of 0.001 vol.%, where both HTC and CHF were approximately 1.33 times higher than for pure water. For higher concentrations (0.01 and 0.1 vol.%), a deterioration in HTC was observed due to the formation of a thick nanoparticle layer on the heat-transfer surface, which increased thermal resistance. According to the literature, the concentration of added nanoparticles typically does not exceed 0.1 vol.% [7,20]. It is also worth noting that the size and shape of nanoparticles significantly affect heat-transfer performance [12,14,21]. When their size is comparable to the surface roughness of the heater, a reduction in boiling intensity may occur due to a decrease in the number of active nucleation sites [22].

It has already been noted that the application of nanofluids in pool boiling enhances process performance. This results in an increase in the heat-transfer coefficient (HTC) and a shift in the critical heat flux (CHF) toward higher values. This improvement is directly attributed to the higher thermal conductivity of nanoparticles compared to the base fluid itself [9]. As a result, heat transfer from the heating surface to the liquid is facilitated. The thermal conductivity of substances depends on their molecular-level properties. Salhi et al. used density functional theory (DFT) to determine the relationship between the thermal conductivity of nanofluids and quantum chemical parameters. Their study examined water-based nanofluids containing nanoparticles of various metals, such as Ag, Au, Cu, and Al. The results showed that nanofluids containing silver exhibit the highest thermal conductivity, which is associated with the lowest energy gap ($\Delta E_{GAP} = 1.4544$ eV) between the HOMO and LUMO orbitals, as well as low ionization potential and low electron affinity. Moreover, high values of enthalpy, entropy, and heat capacity of silver-based nanofluids promote efficient thermal energy transfer at the atomic level. Understanding these relationships enables the optimization of nanofluid composition and the prediction of their behavior in heat-transfer processes. Nanofluids also indirectly enhance heat-transfer performance through deposition on the heat-transfer surface. This leads to the formation of a porous layer, increasing the number of active nucleation sites for vapor bubbles [12]. Additionally, nanoparticles suspended in the fluid undergo Brownian motion, inducing microconvection. This enhances fluid mixing around vapor bubbles, thereby accelerating heat dissipation within the liquid [14].

The application of nanofluids in heat-transfer processes offers numerous advantages; however, it is also associated with certain limitations that must be carefully considered before practical implementation. When the suspension is not properly stabilized, nanoparticles may undergo agglomeration and excessive deposition on the heat-transfer surface [9,12,13,22]. During prolonged boiling, this leads to the formation of a thick and uneven layer on the heating surface, altering, among others, surface roughness, wettability,

and the density of nucleation sites. As a result, thermal resistance increases and both HTC and CHF deteriorate.

Scientific literature regarding nanoscale boiling heat-transfer enhancement reports serious inconsistencies concerning both the observed trends and the dominant mechanisms responsible for changes in cooling performance [23]. The key discrepancies identified in studies on nanofluids and modified surfaces are discussed in [24] and include: inconsistencies in the heat-transfer coefficient (HTC) [25], divergences in CHF enhancement mechanisms [26], controversies in flow boiling [25,27], and lack of repeatability and time-dependency [28].

In [24], three entirely different outcomes have been documented for tested nanofluids. While, on the one hand, adding nanoparticles significantly increased the HTC, with the effect growing monotonically as nanoparticle concentration increases [29], on the other, in [27], no appreciable difference in boiling performance between pure water and low-concentration nanofluids was recorded. Moreover, in some cases, nanofluids can even decrease the heat-transfer coefficient compared to water [30]. This degradation is attributed to factors like the blockage of nucleation sites by depositing nanoparticles and the creation of additional thermal resistance by the sediment layer.

Traditional studies often show that while nanofluids enhance CHF, they simultaneously degrade HTC due to the thermal resistance of deposited nanoparticle layers [31–33]. Conversely, surfactant solutions typically improve HTC but lead to a significant drop in CHF. The hybrid approach utilized in [29] successfully improves both parameters. The hybrid nanofluids increased the HTC by 1.16 to 1.79 times compared to pure water. This is attributed to reduced surface tension, which initiates more nucleation sites, and the biosurfactant's ability to keep particles suspended, minimizing thermal resistance. On the other hand, the CHF increased by 1.41 to 1.61 times. This is driven by the formation of a porous deposition layer that enhances surface wickability and wettability.

Moreover, numerous prior studies have addressed thermophysical properties, evaporation kinetics, or interfacial phenomena separately, rather than investigating these aspects within a unified experimental framework [34,35]. Therefore, there is a clear need for systematic experimental studies that combine the accurate determination of key thermophysical properties of working fluids, including thermal conductivity, specific heat capacity, and latent heat of evaporation [36]. In the case of nanofluids, such investigations should be further extended to account for the effects of nanoparticle concentration and interparticle interactions. In particular, the behavior of nanofluids remains insufficiently understood, as their combined effects cannot be directly inferred from those of the base fluids.

The stability of nanoparticle suspensions can be quantitatively assessed using the zeta potential, which describes the electrical potential at the slipping plane between a solid particle and the surrounding electrolyte solution. The electric charge accumulated on the surface of nanoparticles causes electrostatic repulsion, limiting agglomeration. It is generally accepted that an absolute zeta potential value $|\zeta| > 60$ mV indicates excellent stability, while $|\zeta| > 30$ mV corresponds to good physical stability [15,37].

The addition of nanoparticles to a base fluid often increases its viscosity. This can be beneficial, as higher viscosity slows down particle sedimentation, improving suspension stability. However, excessive viscosity has adverse effects—it reduces fluid circulation near the heating surface, hinders bubble detachment, and suppresses bubble rise. Furthermore, when the viscosity of the nanofluid increases compared to that of water, the resulting higher flow resistance and pressure drop raise the required pumping power and can diminish heat-transfer efficiency (for instance, by lowering the Reynolds number), which may counteract the advantages gained from improved thermophysical properties [38]. Consequently, boiling intensity decreases, leading to reduced heat-transfer efficiency.

A significant limitation in the application of nanofluids, particularly in systems requiring long-term reliability and continuous operation, is the risk of corrosion, erosion, and wear of installation components. These phenomena may result in decreased system performance, increased operational costs, and reduced equipment lifetime [12,14]. Environmental impact is also an important consideration. Therefore, nanofluids should be produced, used, and disposed of in a safe manner, in accordance with applicable regulations and the principles of green chemistry. Finally, the overall cost of nanofluid preparation and stabilization must be weighed against the achieved improvement in heat-transfer performance. In some cases, the increase in HTC or CHF may not justify the high costs associated with their production and implementation in practical systems.

In summary, nanofluids demonstrate significant potential for enhancing heat transfer during pool boiling, primarily due to an increased number of nucleation sites, improved thermal conductivity, and modified wettability of the fluid. However, effective utilization of nanofluids requires careful selection of particle concentration and size, as well as proper stabilization of the suspension to avoid adverse effects such as agglomeration and excessive deposition on the heating surface. With appropriate optimization, nanofluids can provide a noticeable enhancement in heat-transfer performance, enabling the design of more compact and lightweight heat exchangers, which is particularly important for applications in miniaturized electronic systems. Moreover, improved thermal stability of the system can reduce overheating of components, resulting in extended device lifetime and lower operational costs [4].

In this study, the effect of silica–water nanofluids on pool boiling heat transfer over a flat copper surface was presented. In response to challenges, the present study also provides a unified experimental investigation combining the determination of key thermophysical properties of nanofluids—thermal conductivity, specific heat capacity, and latent heat of evaporation—with an analysis of their heat-transfer performance under nucleate boiling conditions. This integrated approach enables a direct correlation between thermophysical properties and boiling heat-transfer behavior.

Changes in HTC and CHF were investigated for different nanoparticle concentrations and compared with the base fluid. To evaluate the stability of the prepared nanofluids, their zeta potential was measured. The obtained results were compared with data available in the literature reported by other authors.

2. Materials and Methods

2.1. Preparation of Nanofluids

Silicon dioxide (SiO_2) nanoparticles in the form of nanopowder supplied by ALDRICH Chemistry (USA) were used for this study. According to the manufacturer, the average particle size ranges from 10 to 20 nm and was determined using the Brunauer–Emmett–Teller (BET) method. The purity of the nanopowder is 99.5% with respect to metallic impurities. Deionized water with an electrical conductivity of 0.003 mS cm^{-1} was used as the base fluid. The remaining properties of the mixture components are listed in Table 1.

Using the two-step method, SiO_2 –water nanofluids with different weight concentrations (0.01%, 0.05%, 0.1%, 0.5%, and 1% wt.) were prepared. The procedure began with weighing appropriate amounts of nanoparticles using the electronic scale of high accuracy and sensitivity (0.001 g and 0.0001 g, respectively), followed by their addition to a measured quantity of deionized water. To ensure uniform dispersion of nanoparticles in the fluid, the resulting suspension was mixed using a mechanical stirrer for approximately 30 min at a rotational speed of about 400 rpm.

Table 1. Thermodynamic properties of the suspension components: SiO₂ nanoparticles and water [39].

Property	SiO ₂ Nanoparticles	Water ¹
d_a , nm	10–20	–
ρ , kg m ^{−3}	2200–2600	959.0 (ρ_l) 0.60 (ρ_v)
i_{lv} , kJ kg ^{−1}	–	2251
λ , W m ^{−1} K ^{−1}	1.4	0.6
c_p , J kg K ^{−1}	705	4200
ν , mm ² s ^{−1}	0.9026	0.296
μ , Pa s 10 ^{−6}	–	284
σ , N m ^{−1}	–	0.06
ϵ , F m ^{−1}	–	78.5 ²
Color	White	Transparent

¹ at $T_{sat} = 373$ K, $p = 101.3$ kPa; ² at $T = 298$ K.

Subsequently, the samples were subjected to ultrasonication for approximately 3 h using an ultrasonic bath operating at a frequency of 40 kHz and a power of 120 W. The high-frequency ultrasonic waves induce cavitation, leading to the formation of microscopic vapor bubbles in the fluid. These bubbles rapidly collapse, generating local pressure fluctuations and intense particle collisions. This process effectively breaks down agglomerates and enables the formation of a stable and homogeneous nanofluid.

Uncertainty Analysis of Gravimetric Nanofluid Preparation

The uncertainty analysis focused on the gravimetric preparation of mono- and hybrid nanofluids, as the weighing process has the greatest influence on the accuracy of the final nanoparticle concentration. Since the nominal concentration is determined solely from mass measurements, the uncertainty analysis was performed for the gravimetrically determined mass fraction.

Mixing and ultrasonication affect nanoparticle dispersion, agglomeration, and colloidal stability but, assuming no material losses or liquid evaporation, they do not alter the nominal concentration. Therefore, these preparation steps were not included in the uncertainty budget. The uncertainty was evaluated according to the law of propagation of uncertainty described in [40,41]. The combined standard uncertainty of the nanoparticle mass fraction was determined according to the law of propagation of uncertainty:

$$w = \frac{m_{np}}{(m_{np} + m_{bf})}, \quad (1)$$

the combined standard uncertainty of the mass measurement was calculated as follows:

$$u(m) = \sqrt{[u_{cal}^2 + u_{res}^2 + u_{rep}^2 + u_{drift}^2]}. \quad (2)$$

where: u_{cal} is the standard uncertainty associated with calibration, u_{res} is the uncertainty due to the balance resolution, u_{rep} represents the repeatability of mass measurements, and u_{drift} is the uncertainty associated with balance drift.

The uncertainty of the nanoparticle concentration was calculated according to:

$$u_{c(w)} = \sqrt{\left\{ \left[\frac{m_{bf}}{(m_{np} + m_{bf})^2} \cdot u(m_{np}) \right]^2 + \left[\frac{m_{np}}{(m_{np} + m_{bf})^2} \cdot u(m_{bf}) \right]^2 \right\}}. \quad (3)$$

The standard uncertainty expressed in weight percentage was calculated as follows:

$$u_{c(w\%)} = 100 \cdot u_{c(w)} \quad (4)$$

The expanded uncertainty was determined from:

$$U(w\%) = k \cdot u_{c(w\%)} \quad (5)$$

where $k = 2$ is the coverage factor corresponding to an approximate confidence level of 95%.

The results of the uncertainty analysis for the gravimetric preparation of SiO₂/water nanofluids are summarized in Table 2. The uncertainty budget was established based on the propagation of uncertainty associated with mass measurements performed using an analytical balance during the preparation of 100 g nanofluid samples.

Table 2. Uncertainty budget for the gravimetric preparation of SiO₂/water nanofluids (100 g of suspension).

SiO ₂ conc. (wt.%)	SiO ₂ Mass (g)	Water Mass (g)	u_c (wt.%)	U (wt.%), ($k = 2$)	Relative Expanded Uncertainty (%)
0.05	0.050	99.950	0.000408	0.000816	1.632
0.10	0.100	99.900	0.000408	0.000816	0.816
0.50	0.500	99.500	0.000406	0.000812	0.162
1.00	1.000	99.000	0.000404	0.000808	0.081

The calculated uncertainty budget demonstrates that the gravimetric preparation procedure is characterized by a nearly constant absolute expanded uncertainty, ranging from 0.000808 to 0.000816 wt.%. Consequently, the relative expanded uncertainty decreases with increasing nanoparticle concentration, from 1.63% at 0.05 wt.% to 0.08% at 1.00 wt.%. This confirms that the proposed preparation procedure ensures reliable and reproducible nanoparticle concentrations over the investigated concentration range.

2.2. Zeta Potential and pH Measurements

To determine the stability level of the obtained aqueous suspensions of silicon oxide, zeta potential measurements were performed. A Zetasizer Nano ZS (Malvern Panalytical, Malvern, Worcestershire, UK) was used (Figure 1).



Figure 1. Zeta potential measurement setup.

The measurement is based on electrokinetic excitation of particles in an electric field and determination of their electrophoretic velocity, which is then converted into the zeta potential value (ζ) using the Helmholtz–Smoluchowski Equation (6) [42]:

$$\frac{v_e}{E} = \frac{\varepsilon \zeta}{\mu}. \quad (6)$$

The zeta potential was measured immediately after the sonication process used for nanofluid preparation. For two selected concentrations, the change in zeta potential two weeks after preparation was also examined. Approximately 1 mL of liquid was introduced into the measurement cuvette, starting with the lowest concentration. The experiments were carried out at 25 °C. Each measurement was repeated at least three times, and the final result was reported as the mean value.

Additionally, the pH of the nanofluids was determined using a Testo 206 pH meter fitted with a pH2 (Testo Sp. Z o.o., Poland) penetration probe, which enabled evaluation of their chemical stability and the reproducibility of the preparation conditions.

2.3. Thermodynamic Properties of Nanofluids

The heat of vaporization, i , and the saturation temperature, T_{sat} , were measured using a heat-flux Differential Scanning Calorimeter (DSC 214 Polyma, NETZSCH, Cracow, Poland), as shown in Figure 2. The experimental parameters were as follows: temperature range 30–160 °C, heating rate 10 K min^{−1}, sample mass 10–15 mg, gas flow rate 40 mL min^{−1}, crucible type Concavus Al with a pierced lid, and purge gas nitrogen (99.9992% purity).



Figure 2. Measuring station for testing the heat of vaporization—differential scanning calorimeter (DSC 214 Polyma, NETZSCH).

The calorimeter was calibrated following the European standard [43], using reference substances such as adamantane, cyclopentane, distilled water, tin, indium, zinc, and bismuth, with sample masses between 3 and 10 mg. The expanded measurement uncertainties were ± 0.3 °C for the saturation temperature and ± 20 J g^{−1} for the enthalpy of vaporization.

The onset and endset temperatures of the evaporation peak were determined using standard tangent intersection methods. The latent heat of vaporization was then calculated

by numerical integration of the corrected heat flow signal over the temperature interval corresponding to the phase change and normalized with respect to the sample mass:

$$i = \frac{1}{m} \int_{t_1}^{t_2} (\dot{q}_{\text{sample}} - \dot{q}_{\text{base line}}) dt, \quad (7)$$

where m denotes the mass of the sample, $\dot{q}_{\text{sample}}$ represents the obtained heat flow, $\dot{q}_{\text{base line}}$ corresponds to the baseline signal, and t_1 , t_2 denote the limits of integration corresponding to the onset and endset of the phase transition. The uncertainty in determining the latent heat is assessed to be about $\pm 1\%$, as inferred from the instrument specifications and the reproducibility of the measurements.

The specific heat capacity and conductivity of investigated nanofluids were determined using the Laser Flash Analysis technique (LFA 467, NETZSCH). In this method, a short heat pulse is applied to one side of the sample, and the resulting temperature response is recorded on the opposite surface. Based on the transient temperature curve, the thermal diffusivity α_{th} is directly obtained.

The specific heat capacity c_p was determined using a comparative method, in which the temperature rise of the sample is evaluated relative to a reference material with known properties. This approach enables the calculation of c_p from the measured thermal response and sample mass.

The thermal conductivity λ was subsequently calculated from the relationship:

$$\lambda = \alpha_{th} \rho c_p. \quad (8)$$

All measurements were carried out under controlled temperature conditions, and each sample was tested at least three times. The expanded uncertainty of the specific heat capacity determination was estimated at $\pm 8\%$.

The density of the nanofluids under investigation was obtained using a mass-based mixing rule that accounts for the nanoparticle mass fraction as follows:

$$\rho_{nf} = \frac{1}{\frac{w}{\rho_{np}} + \frac{1-w}{\rho_{bf}}}. \quad (9)$$

The density and additional properties of the SiO₂ nanoparticles were supplied by the manufacturer, Sigma-Aldrich, obtained from the Safety Data Sheets (SDS), and are summarized in Table 1.

Since the available correlations for nanofluid viscosity are formulated as a function of the nanoparticle volume fraction, the mass concentrations (0.01, 0.05, 0.1, 0.5, and 1.0 wt.%) were first converted into volume fractions using the densities of SiO₂ nanoparticles and the base fluid:

$$\varphi' = \frac{\varphi / \rho_p}{\varphi / \rho_p + [(1 - \varphi) / \rho_{bf}]}, \quad (10)$$

where: φ' —nanoparticle volume fraction [-]; φ —nanoparticle mass fraction [-]; ρ_p , ρ_{bf} —nanoparticle and the base fluid density, respectively [kg/m³].

The dynamic viscosity of the SiO₂/water nanofluids was then estimated using four widely reported viscosity models, namely the Einstein (Equation (11)), Brinkman (Equation (12)), Batchelor (Equation (13)), and Pak–Cho (Equation (14)) correlations [44] (see Table 3). The predicted viscosity values were subsequently compared to evaluate the influence of the selected correlation on the calculated thermophysical properties. The calculated volume fractions were subsequently used as input parameters for the viscosity correlations presented below.

$$\mu_{nf} = \mu_{bf}(1 + 2.5\phi'), \quad (11)$$

$$\mu_{nf} = \frac{\mu_{bf}}{(1 - \phi')^{2.5}}, \quad (12)$$

$$\mu_{nf} = \mu_{bf} (1 + 2.5\phi' + 6.2\phi'^2), \quad (13)$$

$$\mu_{nf} = \mu_{bf} (1 + 39.11\phi' + 533.9\phi'^2), \quad (14)$$

where: μ_{nf} , μ_{bf} —dynamic viscosity of the nanofluid and the base fluid, respectively [Pa·s].

Table 3. Correlations based dynamic viscosity of SiO₂/water nanofluids.

SiO ₂ % wt.	f [-]	SiO ₂ % wt.	Einstein	Brinkman	Batchelor	Pak–Cho
0.01	0.00004154	0.004154	0.284	0.284	0.284	0.284
0.05	0.00020777	0.020777	0.284	0.284	0.284	0.286
0.10	0.00041566	0.041566	0.284	0.284	0.284	0.289
0.50	0.00208317	0.208317	0.285	0.285	0.285	0.307
1.00	0.00417859	0.417859	0.287	0.287	0.287	0.333

The predicted viscosities obtained using the Einstein, Brinkman, and Batchelor models were nearly identical over the entire concentration range, with differences below 0.01%. For the highest investigated concentration (1 wt.% SiO₂), these models predicted only a slight increase in viscosity, reaching approximately 0.287 mPa·s, which corresponds to an increase of about 1.05% compared with pure water at the same temperature. In contrast, the Pak–Cho correlation predicted a significantly higher viscosity (0.333 mPa·s), corresponding to an increase of approximately 17.3%. Since the investigated nanofluids are characterized by relatively low nanoparticle volume fractions, the Brinkman model was selected for further calculations [45]. This model is widely used for dilute suspensions and provides realistic predictions of nanofluid viscosity within the investigated concentration range.

2.4. Pool Boiling Measurements

The prepared nanofluids were investigated under pool boiling conditions. The experimental setup shown in Figure 3 enabled controlled heat flux input and temperature measurement, allowing for analysis of the boiling process and its parameters.

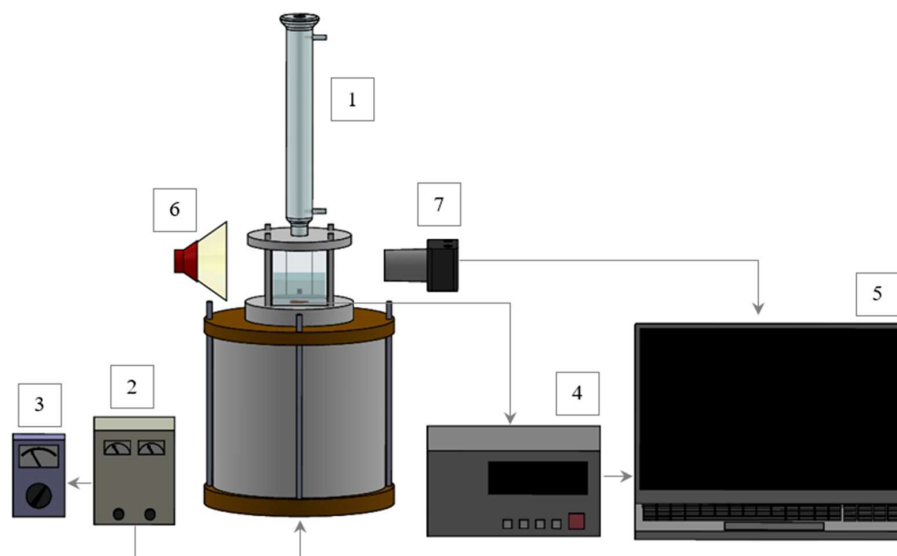


Figure 3. Schematic diagram of the experimental setup. 1—main module, 2—autotransformer, 3—wattmeter, 4—data logger, 5—computer, 6—light, 7—high speed camera.

The main module consists, among other components, of a glass vessel (Figure 4a) filled with approximately 200 mL of the tested liquid. A reflux condenser is attached to the upper part, ensuring vapor condensation and its return to the vessel in liquid form. Its use allows the experiments to be conducted at atmospheric pressure.

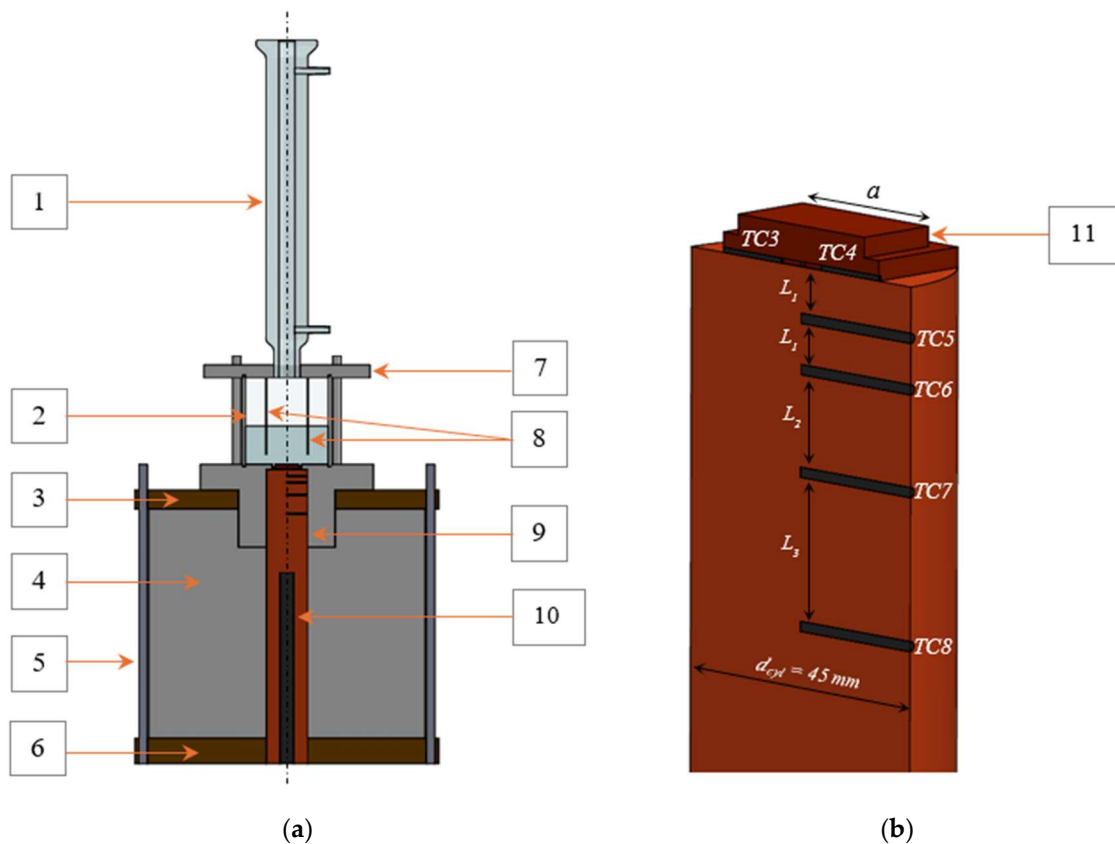


Figure 4. (a) Cross-section of the main module: 1—condenser, 2—glass vessel, 3—Teflon lid, 4—insulation, 5—threaded rod, 6—Teflon base, 7—top flange, 8—thermocouples TC1 and TC2, 9—copper block, 10—cartridge heater; (b) Arrangement of thermocouples in a copper cylinder: 11—test surface, TC3, TC4—thermocouples under the test surface, TC5–TC8—thermocouples in the copper cylinder.

At the bottom of the vessel, a flat copper surface acting as a heat-transfer element, with dimensions of $a \times a$ and an average roughness of $Ra = 0.143 \mu\text{m}$, is mounted. It is soldered with a thin tin layer (approximately 0.05 mm thick) to a copper cylinder ($d_{cyl} = 45 \text{ mm}$). An electric heater is installed along the axis of the cylinder, and its power is controlled using an autotransformer. A wattmeter enables adjustment of the supplied power. The lateral surfaces of the copper cylinder are well insulated; therefore, it is assumed that the heat flux generated by the heater is directed toward the upper part of the cylinder and then to the heat-transfer surface, where energy is transferred to the cooling liquid, causing boiling. During the experiments, K-type thermocouples (NiCr–NiAl) with a diameter of 0.5 mm were used for temperature measurements. Two of them were placed in the liquid (TC1 and TC2), two directly beneath the heat-transfer surface (TC3 and TC4), and the remaining ones (TC5–TC8) were located in the copper cylinder at specified distances from the heat-transfer surface: $L_1 = 5 \text{ mm}$, $L_2 = 10 \text{ mm}$, and $L_3 = 15 \text{ mm}$ (Figure 4b). The data recorded by the sensors were acquired using a FLUKE Hydra Series II data acquisition system (2635A Everett, WA, USA) and subsequently transferred to a workstation computer for further processing.

The pool boiling measurements were initiated with a reference sample, which was deionized water. Subsequently, the prepared nanofluids were tested, and introduced into the measurement vessel immediately after the sonication process. Measurements for nanofluids began with the lowest concentration.

During the experiments, the supplied heat flux was gradually increased, inducing nucleate boiling. Temperature was recorded after reaching steady-state conditions—approximately 10 min after adjusting the autotransformer settings. Measurements were continued until the critical heat flux (CHF) was reached, identified by a sudden increase in temperature beneath the copper heat-transfer surface.

After each experiment, the setup was thoroughly cleaned, with particular attention to the heat-transfer surface. Deionized water and lint-free paper were used to remove any deposited nanoparticles. After each experiment, the test section was thoroughly cleaned, with particular attention paid to the heating surface. First, the surface was rinsed with deionized water to remove residual nanofluid and loosely attached nanoparticles. It was then cleaned using lint-free paper soaked in ethanol to remove any remaining contaminants and ensure complete drying before the subsequent experiment.

The heat-transfer coefficient (α) between the heating surface and the tested liquid was calculated using Equation (15):

$$\alpha = \frac{q}{\Delta T}. \quad (15)$$

The heat flux (q) was determined using Fourier's law (Equation (16)), assuming a thermal conductivity of copper (λ_{Cu}) equal to $380 \text{ W m}^{-1}\text{K}^{-1}$:

$$q = \lambda_{Cu} \frac{T_{TC8} - T_{TC5}}{\delta_{TC8-TC5}} \frac{\pi d_{cyl}^2}{4a^2}. \quad (16)$$

The temperature difference (ΔT) was calculated using Equation (17):

$$\Delta T = \frac{T_{TC3} + T_{TC4}}{2} - q \frac{\delta_s}{\lambda_{Cu}} \frac{T_{TC1} + T_{TC2}}{2}. \quad (17)$$

For the quantities calculated using Equations (15)–(17), measurement uncertainties were estimated using the total differential method. The main sources of uncertainty include the thermal conductivity of copper, temperature measurements in the copper cylinder using thermocouples, the distance between sensors, the cylinder diameter, and the uncertainty associated with thermocouple calibration. The total uncertainty in determining the heat flux is expressed by Equation (18):

$$\Delta q = \sqrt{U_1^2 + U_2^2 + U_3^2 + U_4^2 + U_5^2}, \quad (18)$$

where the individual components correspond to Equations (19)–(23):

$$U_1 = \frac{\partial q}{\partial \lambda} \Delta \lambda, \quad (19)$$

$$U_2 = \frac{\partial q}{\partial \Delta T_{TC5-TC8}} \Delta(\Delta T_{TC5-TC8}), \quad (20)$$

$$U_3 = \frac{\partial q}{\partial \delta_{TC5-TC8}} \Delta \delta_{TC5-TC8}, \quad (21)$$

$$U_4 = \frac{\partial q}{\partial d_{cyl}} \Delta d_{cyl}, \quad (22)$$

$$U_5 = \frac{\partial q}{\partial a} \Delta a. \quad (23)$$

In turn, the uncertainty in determining the heat-transfer coefficient ($\Delta\alpha$) was calculated based on Equation (24):

$$\Delta\alpha = \sqrt{\left(\frac{\partial\alpha}{\partial q}\Delta q\right)^2 + \left(\frac{\partial\alpha}{\partial\Delta T}\Delta(\Delta T)\right)^2}, \quad (24)$$

$$\Delta(\Delta T) = \sqrt{\left(\frac{\partial\Delta(\Delta T)}{\partial q}\Delta q\right)^2 + \left(\frac{\partial\Delta(\Delta T)}{\partial\Delta T_{sat}}\Delta(\Delta T_{sat})\right)^2 + \left(\frac{\partial\Delta(\Delta T)}{\partial\lambda}\Delta\lambda\right)^2 + \left(\frac{\partial\Delta(\Delta T)}{\partial\delta_s}\Delta\delta_s\right)^2}. \quad (25)$$

For the investigated heat flux range, spanning from 58 to 1704 kW m^{−2}, the calculated relative error varied from 15.6% down to 2.4%, clearly indicating a dependence on the heat flux magnitude. In terms of the heat-transfer coefficient, analyzed within the range of 5.3 to 75.8 kW m^{−2}K^{−1}, the relative error was found to be between 4.3% and 26.5%. These results suggest that the model offers satisfactory predictive capability over a broad range of operating conditions, although larger discrepancies are observed at lower heat fluxes.

3. Results and Discussion

3.1. Zeta Potential and pH Measurements

Agglomeration of nanoparticles occurs through various physicochemical interactions, such as van der Waals forces. In an aqueous environment, the surface of silicon oxide exhibits an affinity for forming silanol groups ($\equiv\text{Si}-\text{OH}$). As a result of their dissociation (26), a negative charge is generated on the surface:



This charge enables particles to effectively repel each other via electrostatic interactions. The stability of nanofluids depends on the balance between attractive van der Waals forces and repulsive electrostatic interactions. The dominance of repulsive interactions reduces the tendency of nanoparticles to agglomerate, thereby improving their stability in suspension. The process is strongly dependent on the pH of the medium. At very low pH (approximately 2–3), the reaction equilibrium shifts to the left side of the equation, meaning that only a small fraction of silanol groups dissociate. This leads to the dominance of van der Waals interactions and, consequently, increased particle agglomeration. As the pH increases, electrostatic interactions between nanoparticles become more dominant, which inhibits agglomeration.

Zeta potential measurements allowed for the assessment of the stability of the prepared SiO₂–water suspensions. Figure 5 presents the dependence of zeta potential on nanoparticle concentration.

The measured values, approximately −30 mV, indicate good suspension stability. A slightly lower value (around −25 mV) observed for the 0.01 wt.% concentration suggests moderate stability. This is related to the lower number of particles per unit volume of the base fluid and weaker electrostatic interactions between them. In the study by Salako et al. [42], the zeta potential of silicon oxide nanofluids in deionized water was investigated over a concentration range approximately 100 times lower than in the present work. As expected, the measured values exhibited lower absolute magnitudes, ranging from −3.8 to −26.4 mV. Similarly to the present study, a negative zeta potential was obtained, as the surface of silicon oxide nanoparticles is negatively charged at neutral pH. Increasing the pH could further improve the stability of the SiO₂–water suspension.

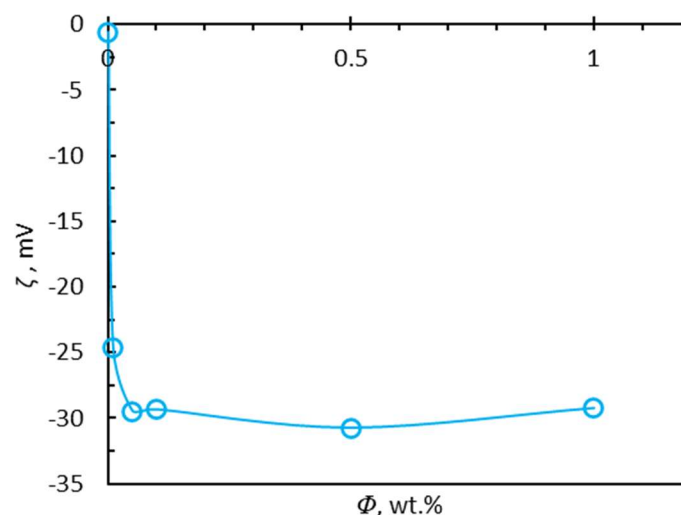


Figure 5. Zeta potential (ζ) of SiO_2 -water nanofluids depending on the concentration (Φ) of nanoparticles, wt.%.

For the two highest SiO_2 concentrations in water (0.5 wt.% and 1 wt.%), the zeta potential was also measured after approximately two weeks from the preparation of the nanofluid. Its absolute value decreased by 2.5% and 3%, respectively, compared to the value measured immediately after preparation. The observed deterioration of the zeta potential indicates a slight reduction in suspension stability over time. This may be caused by the adsorption of trace amounts of positive ions present in the solvent, leading to partial neutralization of the surface charge of the particles. Another possible reason is the sedimentation and aggregation of nanoparticles into larger clusters, which also contributes to the reduction in colloidal stability.

Zeta potential measurements confirm that the applied concentration range of nanofluids enables the formation of stable SiO_2 nanoparticle suspensions in water. The use of lower concentrations could result in less stable suspensions.

In the study by Heidari et al. [27], the zeta potential of SiO_2 nanoparticle suspensions in water (2 wt.%, 20–70 nm) was also investigated over time. The first measurement was performed one week after nanofluid preparation, followed by measurements after two and three weeks. After two weeks, a decrease in the absolute value of the zeta potential of approximately 9% was observed compared to the measurement taken after the first week. The third measurement showed a further decrease of 5.5% relative to the value obtained after two weeks.

The greater tendency for stability reduction observed in their study compared to the present work may be related to differences in water purity and pH. The authors also used a higher concentration of silicon oxide, which increases interparticle interactions and thus accelerates sedimentation and aggregation processes. Differences in the initial zeta potential values should also be considered. Mohammad et al. reported an initial value of -43.8 mV, whereas in the present study, it was approximately -30 mV, which may partly explain the smaller decrease in zeta potential observed over time.

For all tested SiO_2 nanofluid concentrations, the pH was approximately 8, which is consistent with the available literature [46].

3.2. Thermophysical Properties of SiO_2 Nanofluids

The effect of nanoparticle concentration on the enthalpy of vaporization (i), specific heat capacity and boiling temperatures is shown in Figure 6. Measurements were carried out at 20°C , 35°C , 50°C , and 65°C , with values at 100°C obtained by extrapolation.

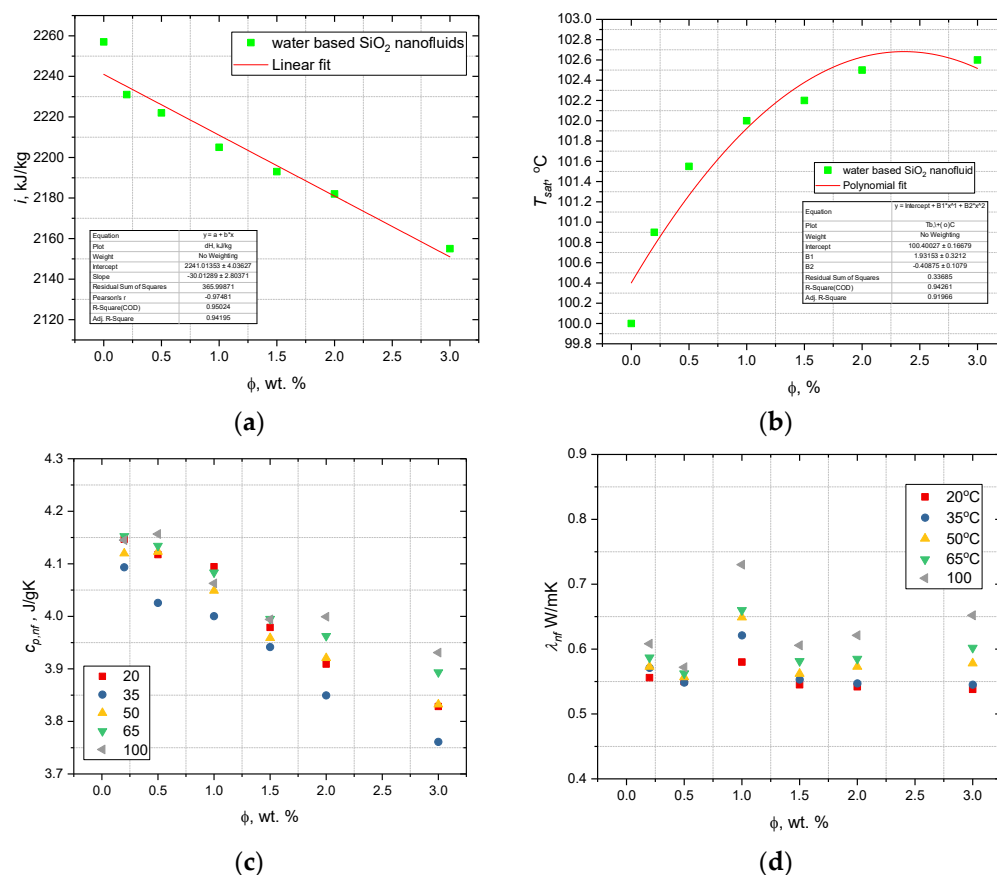


Figure 6. Thermophysical properties of SiO₂ nanofluid as a function of nanoparticle concentration and temperature (a) enthalpy of evaporation (i); (b) saturation temperature, and (c) specific heat capacity (c_p); (d) thermal conductivity (λ_{nf}).

Compared to pure water ($i \approx 2257 \text{ kJ}^{-1} \text{ kg K}^{-1}$) the latent heat of vaporization of SiO₂-based nanofluids shows a gradual decrease with increasing nanoparticle concentration. For the lowest concentration (0.2 wt.%), the reduction is negligible ($\approx 1\%$), whereas for the highest concentration (3 wt.%), it reaches approximately 4.5%. Overall, a reduction of about 3–4% is observed across the investigated concentration range, indicating a systematic but moderate weakening of phase-change energy.

Although many studies have examined thermophysical properties of nanofluids—such as specific heat capacity, thermal conductivity, and viscosity [47]—experimental data on their enthalpy of vaporization are still scarce [48]. Consequently, a direct comparison of i values is often not feasible, which underscores the originality of the present work. The observed trend is qualitatively consistent with the calorimetric study of Bhuiyan et al. [49], who reported a systematic decrease in i for water-based nanofluids containing SiO₂, TiO₂, and Al₂O₃, with reductions reaching 21.96%, 12.38%, and 13–17%, respectively. However, the extent of the decrease observed in this research is considerably smaller. This suggests that the latent heat response is highly sensitive to formulation parameters, including the nanoparticle concentration range, the quality of dispersion, and the specific experimental conditions.

The boiling temperature increases from approximately 100.9 °C to 102.6 °C with increasing SiO₂ concentration, corresponding to a total rise of about 1.7 °C. This indicates a concentration-dependent shift in phase equilibrium, although the overall change remains moderate. This finding aligns with the scarce literature, which reports only slight increases in the boiling point of nanofluids, generally remaining below 3 °C [50].

The specific heat capacity declines as the nanoparticle concentration rises, showing an overall decrease of about 6–8% in the range from 0.2 to 3 wt.%. The impact of temperature is relatively small when compared with the effect of concentration. In addition, incorporating SiO₂ nanoparticles causes a noticeable drop in specific heat capacity relative to pure water, with this effect becoming more pronounced at higher concentrations, though it remains moderate overall. For oxide-based nanofluids comparable to those examined in this work, previous studies show that incorporating nanoparticles usually causes a modest reduction in cp, typically on the order of a few percent, depending on the nanoparticle loading and the composition of the mixture [19,51].

The lowest thermal conductivity performance for SiO₂ water-based nanofluids was observed, with a local maximum noted at 1 wt.%. This is consistent with recent studies indicating that SiO₂-based nanofluids typically yield smaller improvements in thermal conductivity than other metal oxides or carbon-based nanofluid systems [51–53].

While various thermophysical properties of nanofluids have been extensively studied, experimental data regarding their latent heat of vaporization (*i*) remain notably scarce in the global literature. Consequently, the results presented in this study do not merely constitute another dataset, but address a significant research gap, providing unique insights into phase-change energy and underscoring the originality of this work. Furthermore, the scope of this investigation includes an analysis of suspension stability over a two-week duration, which is crucial for evaluating the long-term reliability and practical feasibility of these nanofluids in industrial cooling systems requiring continuous operation.

3.3. Pool Boiling

One of the most commonly applied correlations for describing heat transfer during pool boiling is the Rohsenow correlation. This model assumes that the dominant mechanisms responsible for heat-transfer enhancement are the nucleation, growth, and detachment of vapor bubbles from the heated surface. These phenomena disturb the thermal boundary layer, promote fluid mixing, and consequently intensify heat transfer from the surface to the liquid. Rohsenow introduced a semi-empirical relationship in which the boiling performance is expressed as a function of fluid properties, surface characteristics, and the degree of superheat. The correlation relates heat flux to parameters such as surface tension, thermal conductivity, density, and viscosity of the fluid. A key feature of this model is the empirical coefficient that depends on the specific fluid–surface combination and operating conditions. The Rohsenow correlation can be written as follows (27) [11,54]:

$$\frac{c_p \Delta T}{h_{lv}} = C_{sf} \left[\frac{q}{h_{lv} \mu_l} L_{cap} \right]^{0.33} Pr^n. \quad (27)$$

The exponent $n = 1.7$ was adopted for water, following the original Rohsenow correlation, and $L_{cap} = \sqrt{\frac{s}{g(r_l - r_v)}}$.

This correlation is widely used in the analysis and design of systems utilizing nucleate boiling, especially in industrial applications, power engineering, and electronics cooling. Despite its relatively simple and empirical formulation, it remains a fundamental tool in heat-transfer engineering. A reduction in surface tension facilitates the formation of smaller vapor bubbles and their faster departure from the surface, which increases bubble release frequency and enhances the heat-transfer coefficient (HTC). In semi-empirical formulations such as the Rohsenow correlation, surface tension appears in the denominator, directly affecting the predicted heat flux.

The Rohsenow model does not explicitly account for surface roughness; however, its effect is indirectly reflected in the empirical parameter C_{sf} , which must be determined experimentally. Therefore, although the correlation correctly captures general trends

(e.g., the relative boiling performance of different fluids), accurate representation of the data shown in Figure 7 requires calibration of C_{sf} for a specific surface roughness of $Ra = 0.143 \mu\text{m}$.

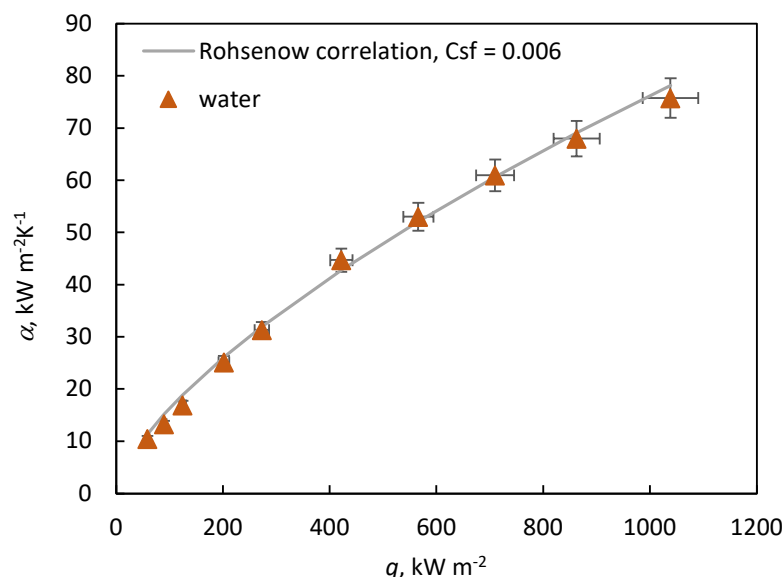


Figure 7. Boiling curves for a surface with roughness $Ra = 0.143 \mu\text{m}$.

The boiling curves presented in Figure 8 can be interpreted using the Rohsenow correlation, which describes the relationship between heat flux and surface superheat ΔT , taking into account fluid properties and surface characteristics such as surface tension, viscosity, and the Prandtl number. The model assumes that boiling intensity is governed by the processes of vapor bubble formation and departure, which are strongly influenced by surface wettability and roughness. The Rohsenow correlation was calibrated only for pure water using the experimentally determined surface parameter $C_{sf} = 0.006$. Due to the progressive modification of the copper surface during nanofluid boiling, separate calibration of C_{sf} values for each SiO_2 concentration was not performed.

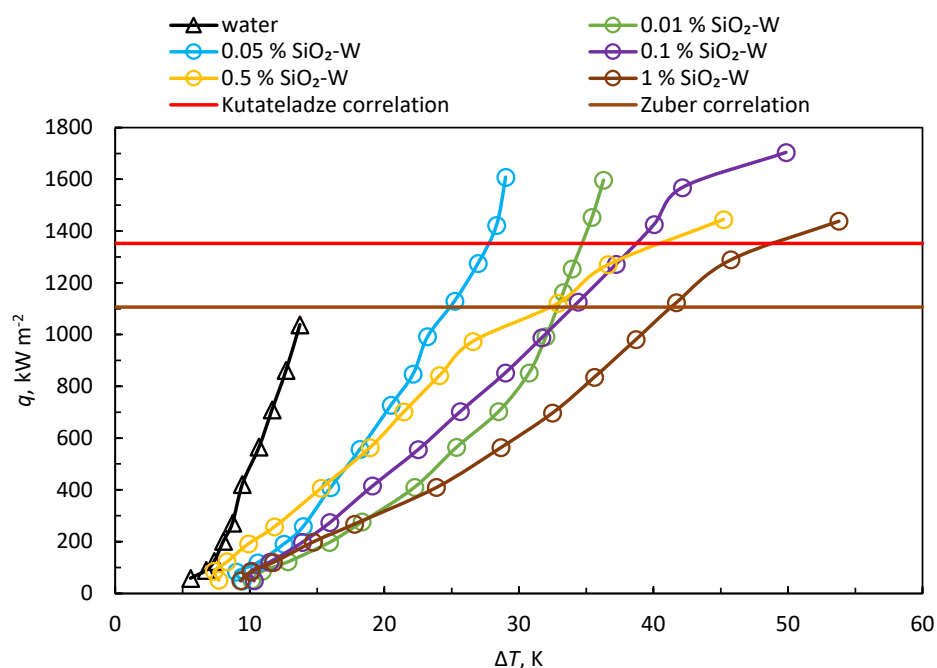


Figure 8. Pool boiling curves: q vs. ΔT .

As a result of the conducted pool boiling experiments of SiO₂–water nanofluids, boiling curves were determined and are presented in Figures 8 and 9. It can be observed that with increasing heat flux, the heat-transfer coefficient (HTC) also increases. The maximum HTC value was obtained for pure water (75.8 kW m^{−2}K^{−1}). In contrast, for nanofluids, this value is lower—for the 0.05 wt.% SiO₂–water concentration, a value of 55.4 kW m^{−2}K^{−1} was obtained. This may be attributed to the deposition of nanoparticles on the heat-transfer surface, as shown in Figure 10. Silicon oxide has significantly lower thermal conductivity than copper; therefore, the formed deposit layer increases the thermal resistance between the surface and the fluid.

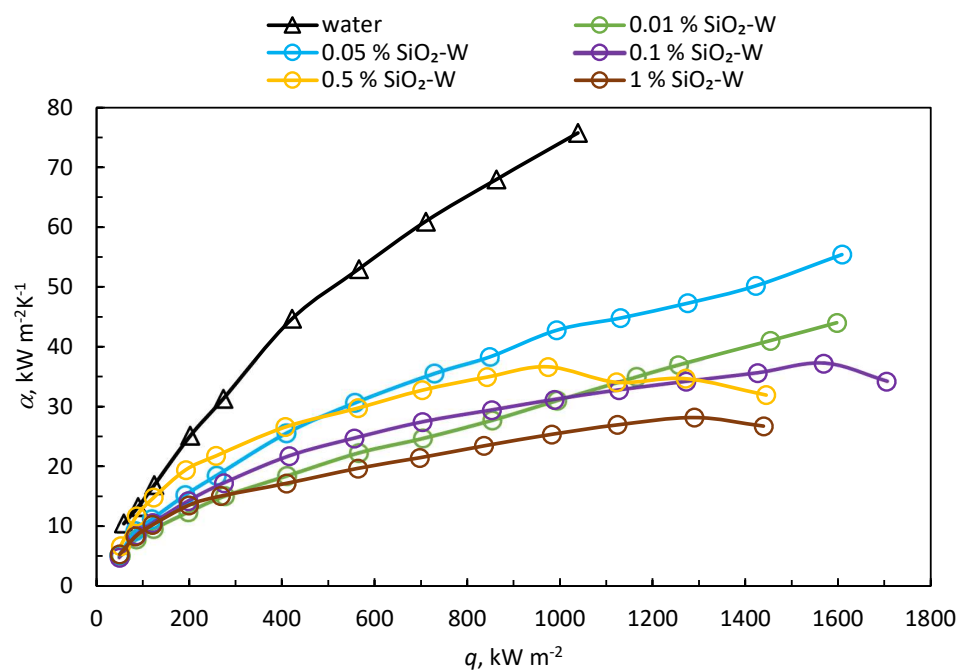
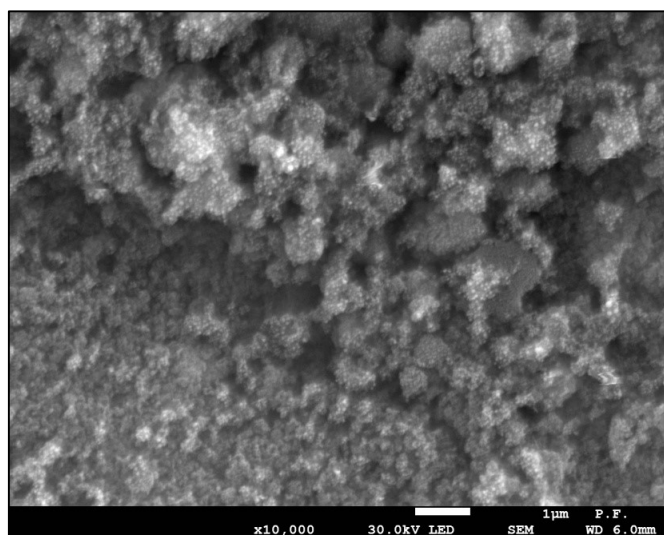
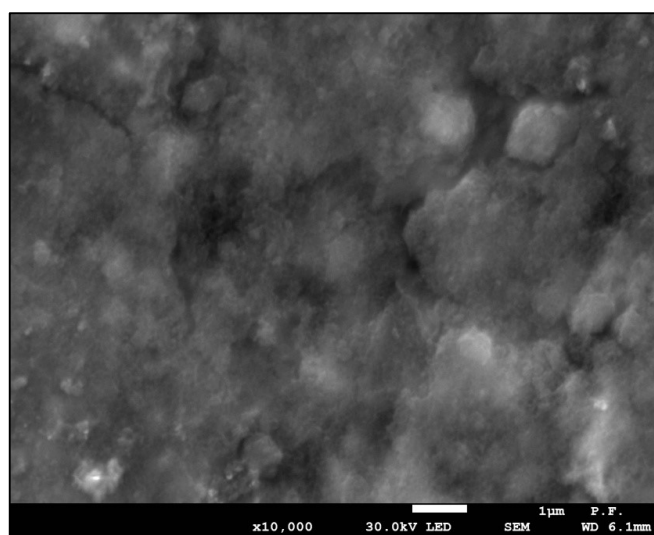


Figure 9. Pool boiling curves: α vs. q .



(a)



(b)

Figure 10. Cont.

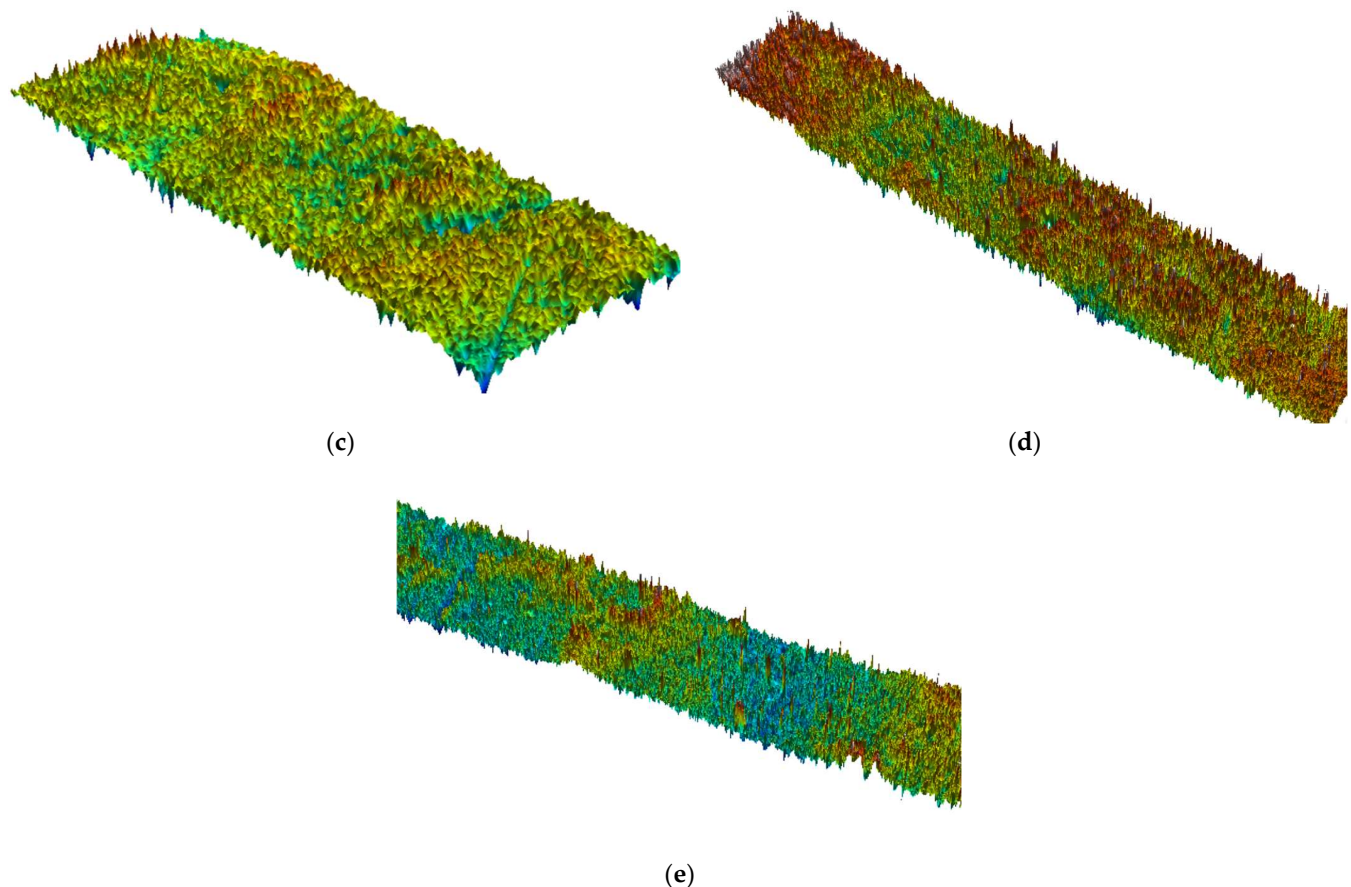


Figure 10. Scanning electron microscope image ($10,000\times$ magnification): (a) agglomerates of silicon oxide nanoparticles deposited on the surface; (b) surface after cleaning with lint-free paper soaked in ethanol prior to the subsequent measurement; Surface topography of the copper sample measured using an optical profilometer: (c) initial surface before pool boiling experiments (deionized water), (d) surface after pool boiling experiments with the SiO_2 /water nanofluid for 0.05 wt.% concentration, and (e) surface after the cleaning procedure.

The applied color map in Figure 10 represents the height distribution of the surface measured using an optical profilometer. Individual colors correspond to different height levels, enabling a qualitative assessment of the topography of the investigated surface.

At high heat fluxes (above 1000 kW m^{-2}), for concentrations greater than or equal to 0.1 wt.%, a decline in the boiling curves toward lower HTC values can be observed. This is associated with increased nanoparticle deposition on the heat exchanger surface due to higher SiO_2 concentrations in water. For lower concentrations, this effect is not noticeable, and the curves exhibit an increasing trend throughout the entire range.

At the same time, the addition of nanoparticles to the base fluid leads to a significant increase in the critical heat flux (CHF) compared with the base fluid. For deionized water, the CHF value was 1038.5 kW m^{-2} , whereas for the nanofluid with a concentration of 0.1 wt.% SiO_2 , it reached 1704.2 kW m^{-2} . This improvement may be associated with changes in the wettability of the heating surface caused by the presence of nanoparticles. As a result, after vapor bubble departure, the liquid can more easily reach the heated area and rewet the surface, delaying the onset of boiling crisis. Additionally, nanoparticle deposition on the heating surface may contribute to the formation of additional active nucleation sites for vapor bubbles. Although SiO_2 nanoparticles exhibit higher thermal conductivity than water, their relatively low concentration in the nanofluid limits the contribution of enhanced thermal conduction to the overall heat-transfer mechanism. Therefore, the

increase in CHF is mainly attributed to improved surface rewetting and modifications of the boiling surface characteristics.

Although the highest improvement in critical heat flux was obtained for the nanofluid with a concentration of 0.1 wt.%, this concentration was also associated with very low HTC values. Therefore, considering the compromise between minimizing the reduction in HTC and increasing CHF, the concentration of 0.05 wt.% can be considered the most favorable among the investigated nanofluids for the studied heat-transfer process.

The hydrodynamic instability model of CHF was first proposed by Kutateladze (Equation (28)) and later further developed by Zuber (Equation (29)). Kutateladze [55] formulated a correlation for the critical heat flux, assuming that the transition to a different boiling regime is caused by hydrodynamic instability of the two-phase boundary layer formed at the heat-transfer surface.

$$\text{CHF} = 0.16 i_{lv} \sqrt{\rho_v} [g(\rho_l - \rho_v)\sigma]^{0.25} \quad (28)$$

Zuber additionally assumed that boiling of the liquid may occur at a temperature lower than the saturation temperature, i.e., under free convection conditions [56].

$$\text{CHF} = 0.131 i_{lv} \sqrt{\rho_v} [g(\rho_l - \rho_v)\sigma]^{0.25} \left(\frac{\rho_l}{\rho_l + \rho_v} \right)^{0.5} \quad (29)$$

The surface morphology analysis of the investigated sample shown in Figure 10a,b was carried out using a field-emission scanning electron microscope (FE-SEM), JEOL Ltd. JSM-7100F, Tokyo, Japan, under constant operating parameters. The observations were performed at an accelerating voltage of 30 kV and a working distance (WD) of 6 mm. Due to the non-conductive nature of the silicon oxide-coated samples, appropriate pre-treatment was required prior to the measurements. Therefore, the sample surfaces were sputter-coated with a thin gold layer of approximately 15 nm using the ion sputter coater JEOL JFC-1100E (JEOL Ltd., Tokyo, Japan) for 2 min before being introduced into the microscope chamber.

Surface roughness measurements were performed using a Talysurf CCI optical profilometer (Taylor Hobson Ltd., Leicester, UK) (Figure 10c–e). Prior to the boiling experiments, the copper specimen was characterized after its initial installation on the test stand. The measured roughness parameters were $Ra = 0.143 \mu\text{m}$ and $Rq = 0.521 \mu\text{m}$. These measurements corresponded to the reference surface used in pool boiling experiments with deionized water.

After completing the boiling experiments with SiO_2 /water nanofluids, the surface roughness increased to $Ra = 0.581 \mu\text{m}$ and $Rq = 0.759 \mu\text{m}$. The observed increase in roughness indicates the formation of a nanoparticle deposition layer on the heating surface during boiling.

Subsequently, the specimen was cleaned and the roughness was measured again. The obtained values decreased to $Ra = 0.399 \mu\text{m}$ and $Rq = 0.503 \mu\text{m}$. Although the cleaning procedure reduced the surface roughness, the Ra value remained higher than that of the initial surface, suggesting that traces of the deposited layer and/or slight permanent modifications of the copper surface persisted after the removal process.

Figure 11 presents images illustrating the process of vapor bubble formation and departure during the boiling of pure water and SiO_2 water nanofluid. The turbidity of the suspension increases with concentration; therefore, the nanofluid with the lowest concentration (0.01 wt.%) was selected for comparison. The image sequence is shown for increasing heat flux values—ranging from 58.6 to 1038.5 kW m^{-2} , for water and from 51.7 to 1597.3 kW m^{-2} for the nanofluid. The bubbles formed during boiling in pure water are

small, fine, and occur in large numbers. In the nanofluid, intensive boiling begins at higher heat fluxes. The vapor bubbles are larger and tend to coalesce, forming bigger bubbles.

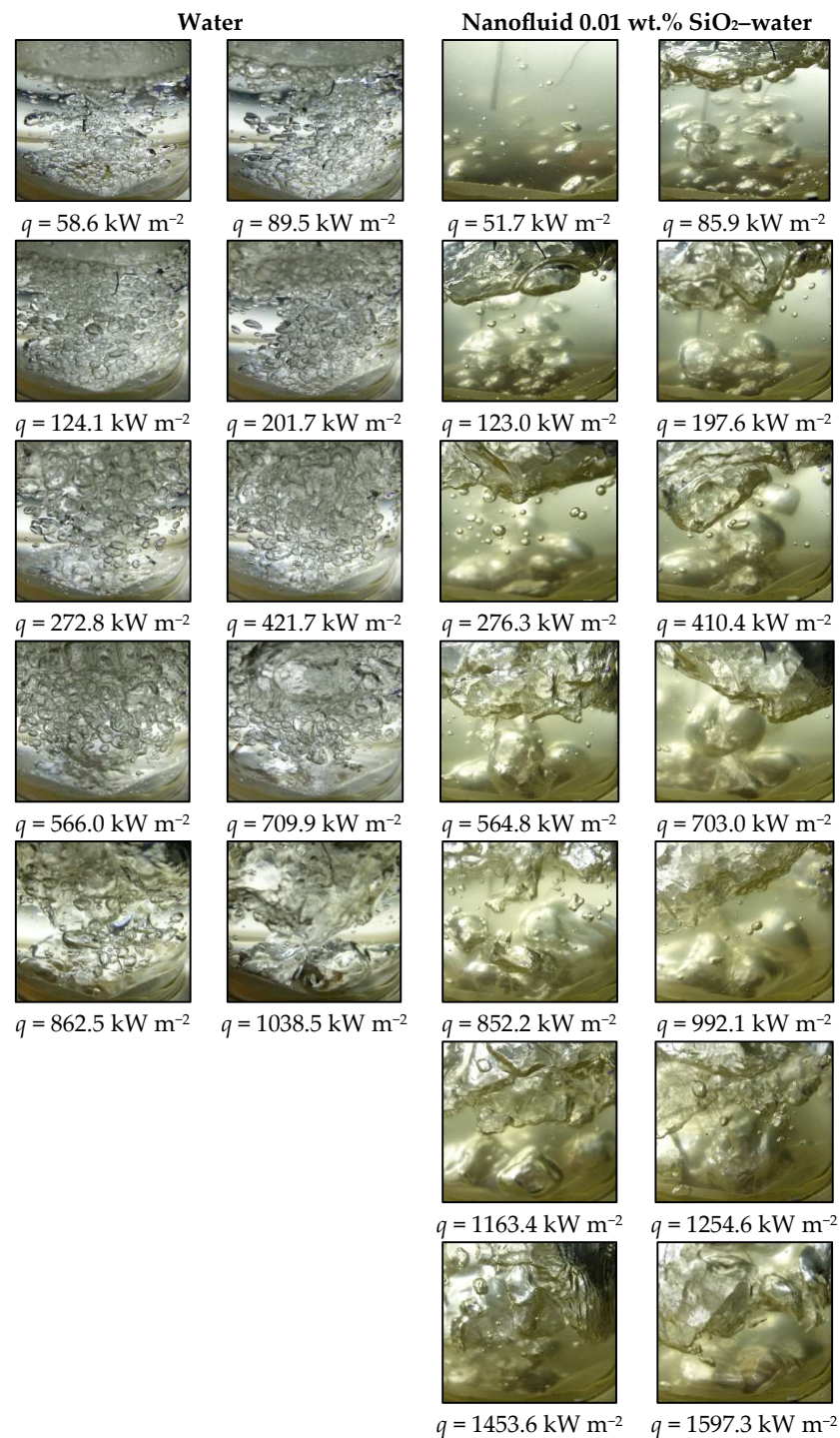


Figure 11. Visualization of pool boiling process on the copper, plain surface for deionized water and 0.01 wt.% SiO₂-water at different heat fluxes, q .

It can therefore be concluded that the nanoparticles did not increase the number of active nucleation sites but instead altered the conditions for bubble growth and coalescence. This may be attributed to an increase in fluid viscosity after the addition of SiO₂ nanoparticles. As a result of the change in viscosity, bubbles detached from the heat-transfer surface slightly more slowly.

It can be observed that with increasing concentration of the SiO₂–water nanofluid, the heat-transfer coefficient tends to deteriorate. An exception to this trend is the lowest concentration (0.01 wt.%), for which the maximum HTC over the entire heat flux range ($44.0 \text{ kW m}^{-2}\text{K}^{-1}$) is lower than that obtained for the 0.05 wt.% concentration ($55.4 \text{ kW m}^{-2}\text{K}^{-1}$). This behavior may be attributed to the lower stability of the 0.01 wt.% nanofluid, as indicated by zeta potential measurements. Reduced stability promotes increased nanoparticle agglomeration, which limits the number of active nucleation sites and promotes the formation of a deposition layer on the heating surface, thereby increasing thermal resistance at the phase boundary. As a result, the dynamics of bubble formation and detachment during boiling are adversely affected, leading to a reduction in heat-transfer performance.

The relationship between the suspension stability and the HTC is considered a causal effect. Quantitative evidence from zeta potential measurements confirms that the 0.01 wt.% concentration exhibits lower stability (approximately -25 mV) compared to the 0.05 wt.% concentration (approximately -30 mV). This lower electrokinetic stability promotes more intense nanoparticle agglomeration and settling. Consequently, a more irregular and resistive deposition layer is formed on the copper surface, which directly blocks active nucleation sites and reduces the HTC to $44.0 \text{ kW m}^{-2}\text{K}^{-1}$, whereas the more stable 0.05 wt.% nanofluid maintains a higher HTC of $55.4 \text{ kW m}^{-2}\text{K}^{-1}$.

An important issue associated with the use of nanoparticles in heat-transfer processes is their long-term stability in suspension and the possibility of changes in thermal characteristics during prolonged system operation. Therefore, for a selected concentration of SiO₂ nanoparticles in water (0.05 wt.%), a study was conducted involving repeated pool boiling cycles by gradually increasing the heat flux (C1–C5 (h)) and subsequently decreasing it (C1–C5 (c)). This made it possible to examine the occurrence of heat-transfer coefficient hysteresis and to assess the repeatability of the process. Five pool boiling cycles were performed for heat fluxes ranging from approximately 70 kW m^{-2} to approximately 1440 kW m^{-2} . During the experiments, the critical heat flux (CHF) was intentionally not reached in order to avoid transition to film boiling, which would have prevented analysis of repeatability and hysteresis within the nucleate boiling regime. The results obtained for the selected boiling cycles are presented in Figure 12.

The measurements carried out over five pool boiling cycles revealed no significant changes in the heat-transfer characteristics. The curves obtained for successive cycles were nearly identical, indicating good repeatability of the process. In the first measurement cycle during the increase in heat flux (C1 (heating)), slightly higher values of the heat-transfer coefficient (HTC) were observed in the low heat flux region compared with the subsequent cycles. This may be interpreted as an effect of the system reaching steady operating conditions, during which the heating surface had not yet become fully stabilized. The amount of nanoparticles deposited on the surface may still have been relatively small, resulting in lower thermal resistance and, consequently, slightly higher HTC values. In addition, it can be observed that with each successive cycle, the HTC values at high heat fluxes were slightly higher. The variation in the maximum HTC values over the five measurement cycles was 10.7%. The heat-transfer experiments were conducted without applying a cleaning procedure for the heating surface between consecutive measurement cycles. This approach enabled the assessment of the influence of the gradually developing deposition layer on the boiling characteristics and demonstrated an increase in the additional thermal resistance associated with the presence of this layer. During intense boiling, vapor bubbles detach from the heat-transfer surface in a highly dynamic and vigorous manner. This phenomenon may promote the partial removal of adsorbed SiO₂ nanoparticles from the surface, thereby exposing new nucleation sites. Nevertheless, these changes were minor and remained

within the range of measurement uncertainty; therefore, it cannot be conclusively stated whether they are statistically significant.

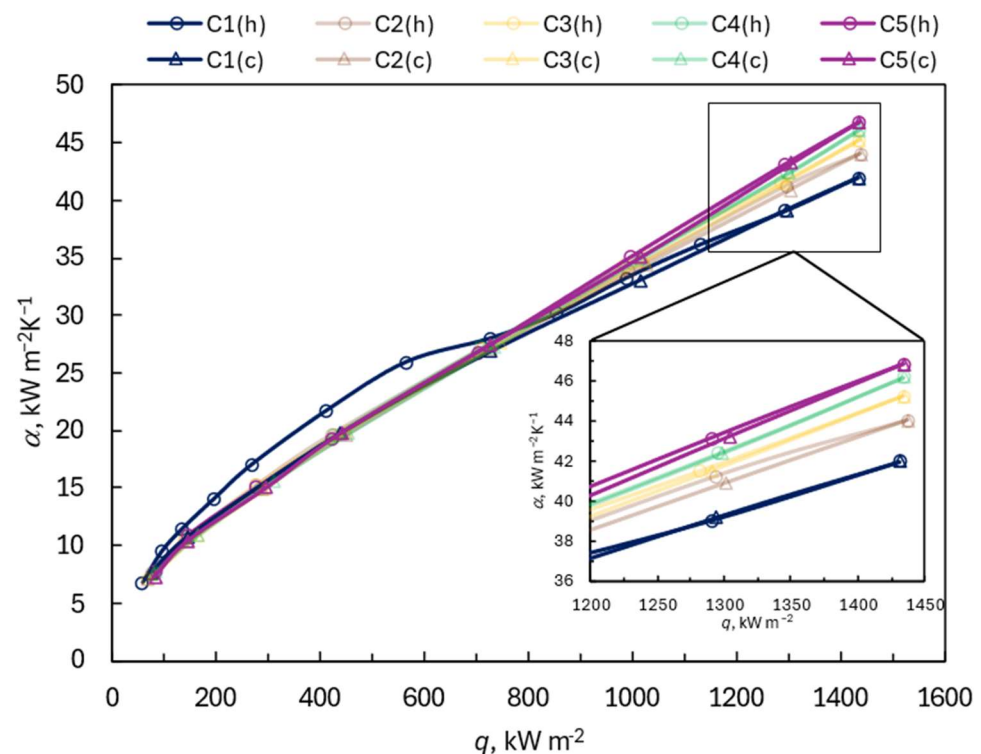


Figure 12. Pool boiling curves: α vs. q for 0.05 wt.% SiO₂—water.

No hysteresis effect was observed, as the curves corresponding to increasing and decreasing heat flux followed nearly identical paths and largely overlapped. The obtained results indicate good stability and high reversibility of the bubble nucleation and departure mechanisms within the investigated range. The absence of significant differences between the curves also suggests that no substantial or permanent changes occurred on the heating surface during the experiment, nor were the nucleation conditions significantly modified by the presence of nanoparticles. Thus, the state of the system remained largely independent of the previous thermal history.

Table 4 presents a comparison of pool boiling studies using SiO₂ nanoparticles. In the present study, a decrease in the heat-transfer coefficient (HTC) by 46–67% compared to the pure base fluid was observed, along with an increase in the critical heat flux (CHF) of 64%.

Table 4. Comparison of research on pool boiling using SiO₂ nanofluids.

Author	Surface	Base Fluid	Nanoparticle Size, nm	Concentration of Nanoparticles	HTC	CHF
This study	Plain, copper	W	10–20	0.01–1 wt.%	↓ 46–67%	↑ 64%
Ajeeb et al. [57]	Ni-Cr wire	EG/W (15/85 vol.%)	20	0.05 vol.%	↑ ~8%	↑ 48%
Lee et al. [58]	Flat type of 304 stainless steel	W	8–100	0.1–10 ppm	Not reported	↑ 87%
Rostamian et al. [59]	Plain	W	7–14	0.005–0.01 vol.%	↑ for <0.01 vol.%	↑ 48%

Ajeeb et al. [57], using particles of similar size and concentrations, obtained a smaller increase in CHF, equal to 48%. However, they also reported a slight enhancement in HTC.

This difference may be attributed to the composition of the base fluid. The addition of ethylene glycol to water modifies its thermophysical properties by increasing viscosity. Nanoparticles may disperse more uniformly in such a mixture, without forming agglomerates and without undergoing as significant deposition on the heating surface as observed in the present study. In turn, Lee et al. [58] reported an even greater increase in CHF, reaching as much as 87%. Such a favorable result was achieved by using very low SiO₂ concentrations in water, at the ppm level, along with larger nanoparticle sizes. Rostamian et al. [59] observed an increase in HTC for concentrations lower than 0.01 vol.%, and reported a CHF enhancement of 48%. The presented results suggest that the improvement in boiling performance strongly depends on the selection of nanoparticle concentration, particle size, as well as the addition of other substances that modify the properties of the base fluid.

4. Conclusions

The application of SiO₂ nanoparticles in water significantly affects the pool boiling process and heat-transfer performance. A decrease in the heat-transfer coefficient (HTC) compared to the pure base fluid was observed (a decrease from 46% to 67%), accompanied by a substantial increase in the critical heat flux (CHF)—up to 64%, reaching a maximum value of 1704.2 kW m^{−2}. The deposition of nanoparticles on the heating surface leads to the formation of a layer with lower thermal conductivity, increasing thermal resistance and reducing HTC, particularly at higher concentrations. At the same time, the presence of nanoparticles promotes the formation of additional nucleation sites, resulting in enhanced CHF.

The stability of the nanofluid, determined based on zeta potential measurements, plays a key role in its performance. Lower stability leads to particle agglomeration, a reduction in active nucleation sites, and the formation of a deposition layer, all of which deteriorate heat-transfer conditions.

The findings confirm a causal relationship between the electrokinetic stability of the nanofluid and its boiling performance. Quantitative evidence shows that the 0.01 wt.% concentration, characterized by a lower absolute zeta potential (|25| mV), resulted in a lower HTC (44.0 kW m^{−2}K^{−1}) due to enhanced agglomeration. In contrast, the more stable 0.05 wt.% nanofluid (|30| mV) maintained a higher HTC of 55.4 kW m^{−2}K^{−1}.

The analysis of suspension stability over a two-week duration confirmed that the SiO₂ nanofluids maintain high colloidal stability, with absolute zeta potential values decreasing by only 2.5–3.0%. This long-term stability underscores the practical feasibility and reliability of the prepared working fluids for industrial cooling systems requiring continuous and efficient operation.

This study combines boiling curve analysis with independent measurements of thermophysical properties, including latent heat of vaporization, specific heat capacity, and thermal conductivity. Importantly, the experimental results for the latent heat of vaporization address a significant research gap, as such data remain notably scarce in the global literature. This comprehensive and integrated approach not only strengthens the physical interpretation of the results but also underscores the originality and scientific value of this work.

With increasing nanoparticle concentration from 0.01 wt.% to 1 wt.%, a general decline in HTC is observed due to more intense deposition and stronger interparticle interactions. Visual analysis also revealed changes in the boiling mechanism—bubbles become larger, coalesce more frequently, and detach more slowly from the surface.

Comparison with literature data indicates that the effects of nanoparticles strongly depend on their concentration, size, and the properties of the base fluid. Among the

analyzed cases, the optimal concentration was 0.05 wt.% SiO₂, providing a favorable balance between HTC and a significant enhancement in CHF.

To achieve a more comprehensive understanding of the mechanisms responsible for the enhancement in the critical heat flux (CHF) during pool boiling, future work will include a detailed wettability analysis based on contact angle measurements. Particular attention will be paid to comparing the wettability of the heating surface before and after the boiling process, as well as after boiling with the base fluid and the SiO₂/water nanofluid. This analysis will provide a deeper understanding of the influence of nanoparticles on surface modification and help clarify the mechanisms responsible for the observed enhancement in CHF.

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Abbreviations

The following abbreviations are used in this manuscript:

<i>a</i>	width of specimen (m)
BET	Brunauer–Emmett–Teller method
CHF	critical heat flux (W m ^{−2})
<i>c_p</i>	specific heat (J kg ^{−1} K ^{−1})
<i>C_{sf}</i>	empirical coefficient depending on the fluid–surface combination
<i>d</i>	diameter (m)
DFT	density functional theory
<i>E</i>	electric field (V m ^{−1})
ΔE_{GAP}	lowest energy gap (eV)
EG	ethylene glycol
<i>g</i>	gravitational acceleration (m s ^{−2})
<i>h</i>	latent heat (J kg ^{−1})
HTC	heat-transfer coefficient (W m ^{−2} K ^{−1})
<i>i</i>	enthalpy (J kg ^{−1})
<i>L</i>	length (m)
<i>m</i>	mass of the sample (kg)
<i>n</i>	exponent depending on the fluid type (e.g., 1 for organic fluids, 1.7 for water)
<i>q</i>	heat flux (W m ^{−2})
<i>p</i>	pressure (kPa)
Pr	Prandtl number (dimensionless number characterizing heat conduction)
<i>Ra</i>	roughness (mm)

Rq	roughness height (mm)
T	temperature (K)
$TC1...TC8$	thermocouple number
ΔT	surface superheat, difference between surface and liquid temperature bottom (K)
U	uncertainty
v_e	electrophoretic velocity of particles (m s^{-1})
w	mass fraction
W	water
Greek letters	
α	heat-transfer coefficient ($\text{W m}^{-2}\text{K}^{-1}$)
α_{th}	diffusivity (m^2s^{-1})
δ	thickness (m)
Δ	error, uncertainty
ε	dielectric constant of the dispersing phase (F m^{-1})
ζ	zeta potential (mV)
λ	thermal conductivity ($\text{W m}^{-1}\text{K}^{-1}$)
n	kinematic viscosity (m^2s^{-1})
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
Φ	concentration (wt.%)
Subscripts	
a	average
bf	base fluid
Cu	copper
cap	capillary
cyl	cylinder
l	liquid
lv	vaporization
max	maximum
nf	nanofluid
np	nanoparticle
s	specimen
sat	saturated
Sn	tin
v	vapor

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