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Enhancing Heat Dissipation in Microchannel Heat Sinks: A Comprehensive Study on Al_2O_3 Nanoparticle Concentration and Flow Rate Dependencies †

Ngisomudin, Agus Dwi Anggono *, Marwan Effendy and Ngafwan

Mechanical Engineering, Universitas Muhammadiyah Surakarta, Jl. Ahmad Yani, Surakarta 57162, Indonesia; u100180016@student.ums.ac.id (N.); me213@ums.id (M.E.); nga275@ums.id (N.)
* Correspondence: ada126@ums.ac.id or ada126@ums.id; Tel.: +62-271-717417

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Abstract: This study aimed to investigate the influence of Al_2O_3 nanoparticle concentration and flow rate on the convective heat transfer coefficient in a heat sink. A testing apparatus was constructed to examine a microchannel heat sink coupled with an Al_2O_3 nanoparticle fluid. Temperature sensors were strategically placed at the microchannel heat sink's entrance (T-in) and exit (T-out). Furthermore, a heating element (T-heater) was utilized to monitor the temperature of the nanoparticle fluid. This experimental setup allowed for precise temperature measurements in the system. Aluminum oxide (Al_2O_3) nanoparticles were thoroughly dispersed in water for 15 min using a magnetic stirrer, resulting in a uniform mixture with concentrations ranging from 0.2% to 1%. The experiments involved altering the flow rates within the range of 0.2 to 1.4 L per minute, enabling the monitoring of temperature changes (T). The heat transfer coefficient positively correlated with escalating concentrations of Al_2O_3 particles. Incorporating nanoparticles up to a concentration of 1% significantly enhanced the heat transfer coefficient by 17.29%. Additionally, a direct relationship was observed between the heat transfer coefficient and the increase in the flow rate of the Al_2O_3/water nanofluid. Specifically, when the flow rate was increased from 0.2 to 1.4 lpm, a significant enhancement in the heat transfer coefficient of 29.95% was achieved.

Keywords: Al_2O_3; nanofluid; nanoparticle concentration; flow rate; heat sink; microchannel

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1. Introduction

Utilizing electronic devices, including laptops and computers, has become essential for human beings in contemporary society. However, the extensive usage of these devices can lead to elevated temperatures, resulting in a decline in their overall performance. A heat exchanger is imperative to ensure that electronic devices remain at optimal temperatures [1,2].

A heat exchanger is a device that efficiently transfers thermal energy from one system to another without any accompanying mass transfer. It serves the purpose of either cooling or heating, utilizing water as the heat transfer fluid. Optimal heat exchange requires a heat exchanger with suitable dimensions and exceptional performance capabilities. The microchannel heat sink is a commonly employed cooling apparatus for integrated arrangements of electronic devices, primarily utilized to dissipate heat [3,4].

At a heightened intensity, swift agglomeration and friction within cooling installations instigate detrimental wear on pipes, pumps, and bearings. Consequently, microchannels encounter obstructions, impeding their optimal functionality. These challenges were prevalent in the initial iterations of the technology. The escalating trend of device/product miniaturization contributes to the heightened complexity of cooling issues in diverse electronic devices. Consequently, the field of heat transfer is exploring the utilization of nanofluids as a potential solution to address these challenges. The process of dispersing nanoparticles, nanofibers, nanotubes, nanorods, or nanowires in a basic fluid using a combination of solid and liquid phases is commonly called nanofluidization. The size of these nanostructures is typically below 100 nm [5].

The present discourse elucidates that the scientific literature has extensively investigated various types of particles, encompassing metallic particles such as copper (Cu), silver (Ag), calcium oxide (CaO), and gold (Au), alongside non-metallic particles, including silicon carbide (SiC), silicon dioxide (SiO_2), titanium dioxide (TiO_2), zinc oxide (ZnO), and aluminum oxide (Al_2O_3) [6,7]. Water, oil, refrigerant, organic glycol fluid, bio-fluid, polymer solution, and mineral oil are fundamental fluids frequently employed in cooling systems [8]. According to prior studies, it has been reported that the thermophysical properties related to thermal conductivity in fundamental fluids such as water or oil, including viscosity, thermal diffusivity, and the convective heat transfer coefficient, exhibit lower values compared to those observed in nanofluids.

The superior heat transfer efficiency of Al_2O_3/water nanofluids, compared to deionized water nanofluids, can be attributed to the elevated viscosity of the former. This augmented viscosity is a consequence of the deposition of Al_2O_3 nanoparticles on the inner walls of the microchannel, leading to a noticeable enhancement in heat transfer [9]. The nanofluid exhibits a notable enhancement in heat transfer due to its elevated concentration percentage. Specifically, a concentration percentage of 0.25% yields satisfactory outcomes compared to the base liquid, resulting in a substantial reduction in thermal resistance by approximately 32.5% and 26% [10,11].

Various methods can enhance the heat transfer coefficient, including manipulating the dispersion concentration flow rate and adopting nano-sized particles possessing superior thermal conductivity compared to the base fluid [12]. To optimize the convective heat transfer coefficient, the experimenter conducted a series of tests investigating the impact of concentration and flow rate on heat transfer within the heat exchanger.

2. Research Method

The research process commences with the preparation of materials and tools. The material employed comprises nano-sized Al_2O_3 particles and water. The heat exchanger is the designated tool employed for testing purposes. When homogenizing aluminum oxide particles with water at a concentration range of 0.2–1%, a magnetic stirrer is employed for 15 min for every composition.

Nanofluid samples were prepared by combining Al_2O_3/water concentrations of 0.2, 0.4, 0.6, 0.8, and 1% in a total volume of 200 g. The preparation process involved utilizing a magnetic stirrer. The experimental flow rate employed ranged from 0.2 to 1.4 L per minute. The water and Al_2O_3 nanoparticles were mixed for 150 min utilizing a magnetic stirrer.

This study employs a specialized testing apparatus specifically engineered to replicate flow velocity systems to investigate nanofluid performance. Figure 1 presents a graphical representation of the investigation, illustrating a closed flow loop incorporating diverse components. These components include a circulation pump, a flow rate meter, a water cooling block, an air radiator, a thermoelectric cooler, a vibration tank, a plate heater, and temperature sensors.

In this experiment, data was collected utilizing a liquid with a mass of 200 g that was circulated through a closed-loop system. A direct current (DC) pump, capable of a maximum flow rate of 4 L per minute, transports fluid from the mechanical vibration bath to the water block. In the water block, the fluid undergoes heat absorption, directed through the water cooler and thermoelectric cooler (TEC) to facilitate its cooling further. The present system is equipped with multiple sensors interconnected with an Arduino microcontroller and a web-based data acquisition system.

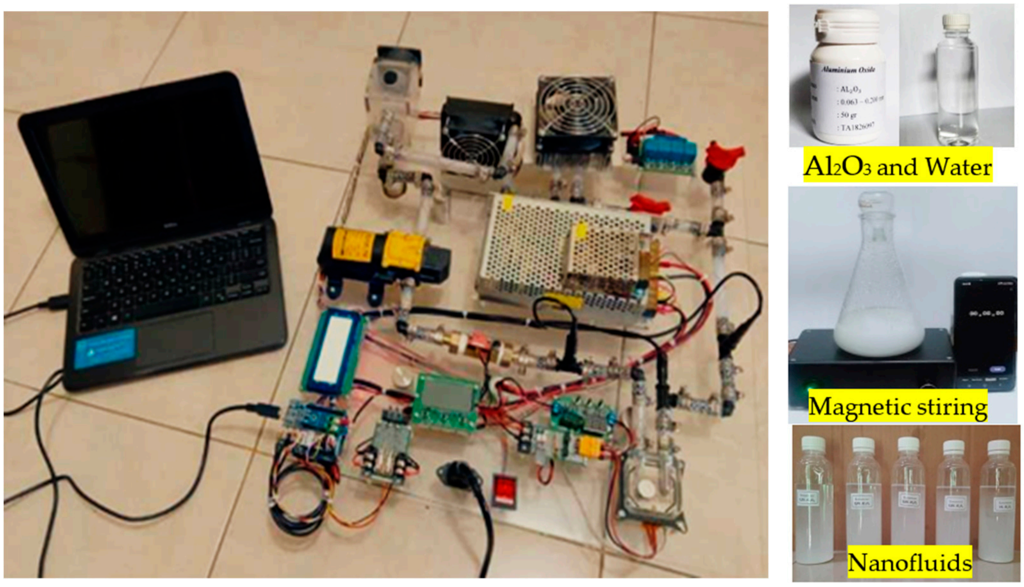

Figure 1. Experimental apparatus for evaluating the performance of nanofluids.

The experiment was conducted for 600 s to ensure comprehensive coverage of all flow rate and concentration volume variations. The sensor readings were automatically recorded and stored as a Comma-Separated Values (CSV) file for subsequent analysis. The obtained data was then processed utilizing a calculation formula within the Excel software (https://www.microsoft.com/en-us/microsoft-365/excel, accessed on 27 February 2024). The acquisition of temperature data from the sensor is constrained by the presence of a comma (,) delineating the subsequent variable as data originating from an alternative temperature sensor. A yellow mark is a visual aid to denote that the abovementioned data corresponds to the sixtieth second.

3. Results and Discussions

3.1. The Convective Heat Transfer Coefficient of Water

During the conducted water test, the heat transfer coefficient exhibited a positive correlation with variations in flow rate, ranging from 0.2 to 1.4 L/minute. Water's observed heat transfer coefficient values were recorded as 0.95, 1.49, 1.82, and 2.49 KW/(m^2K). The experimental data for the convective heat transfer coefficient of water are presented in Figure 2.

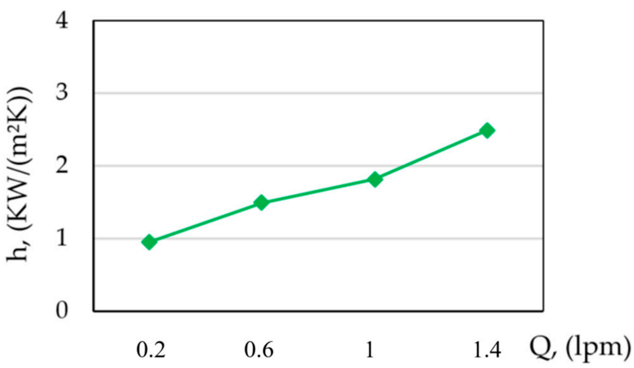

Figure 2. The convective heat transfer coefficient of water.

3.2. The Influence of Varying Concentrations of Al_2O_3 Fractions on the Convective Heat Transfer Coefficient

The thermal performance of water-based solutions has been effectively examined through experimental methods involving Al_2O_3 nanoparticles. The primary metric employed in this study to assess thermal efficiency is the convective heat transfer coefficient. Its determination consists of the utilization of both empirical data and mathematical models. Figure 3 displays the alterations in the convective heat transfer coefficient of Al_2O_3/water nanofluid in response to fluctuations in particle fraction concentration, ranging from 0.2% to 1%. Experimental results demonstrate a positive correlation between the convective heat transfer coefficient and the concentration of particle fraction, suggesting a gradual augmentation in heat transfer with increasing particle concentration.

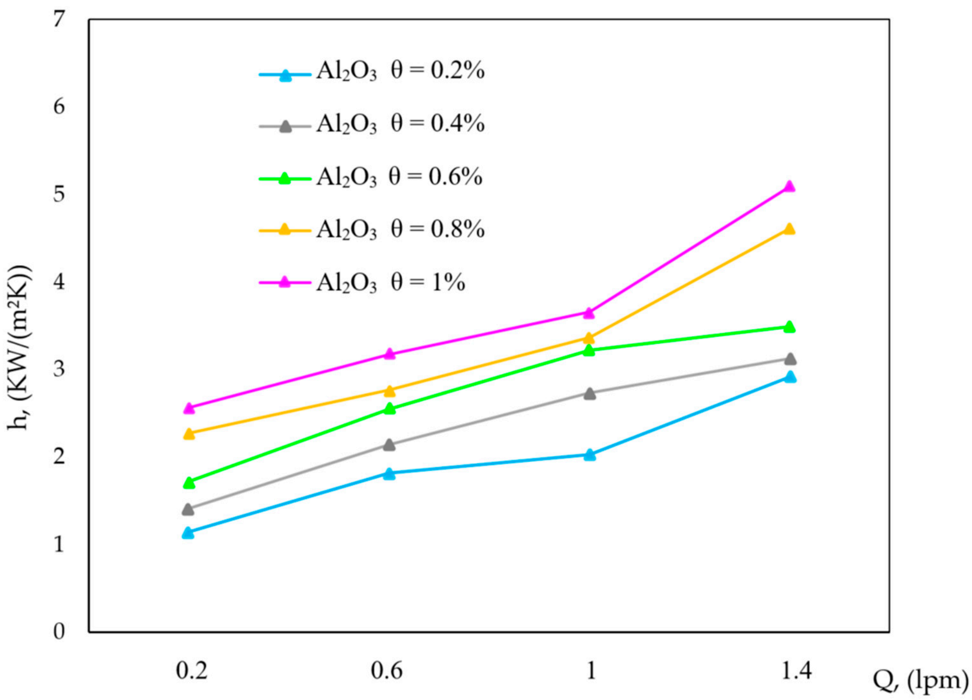

Figure 3. The impact of Al_2O_3 particle fraction concentration.

The heat transfer coefficient exhibited a mean increase of 22.39% upon introducing Al_2O_3 particles at a flow rate of 0.2 L/min. At a flow rate of 0.6 L/minute, the average augmentation in the heat transfer coefficient is 15.06%. At a flow rate of 1 L/minute, the heat transfer coefficient exhibits an average increase of 16.38%. The flow rate of 1.4 L per minute significantly increases the heat transfer coefficient, resulting in an average enhancement of 15.34%. The convective heat transfer coefficient of a nanofluid consisting of Al_2O_3 particles dispersed in water, with a particle fraction concentration ranging from 0.2% to 1%, exhibited an average increase of 17.29%.

3.3. The Relationship between Flow Rate and Convective Heat Transfer Coefficient

The alteration in flow rate, with values of 0.2, 0.6, 1, and 1.4 L/min, within the Al_2O_3-water nanofluid exhibits a discernible impact on the convective heat transfer coefficient. The experimental findings demonstrate a gradual increase in the convective heat transfer coefficient with variations in flow rate, as depicted in Figure 4. At a concentration of 0.2% Al_2O_3, the heat transfer coefficient exhibited a 37.84% increase in response to variations in flow rate. Similarly, at a concentration of 0.4%, the average heat transfer coefficient demonstrated a 31.27% increase.

The convective heat transfer coefficient value displayed an average increase of 27.67% at a concentration of 0.6%. At concentrations of 0.8% and 1%, the average gains were observed to be 26.85% and 26.12%, respectively. The convective heat transfer coefficient of Al_2O_3/water nanofluid, under a flow rate ranging from 0.2 to 1.4 L/min, exhibited a mean enhancement of 29.95%.

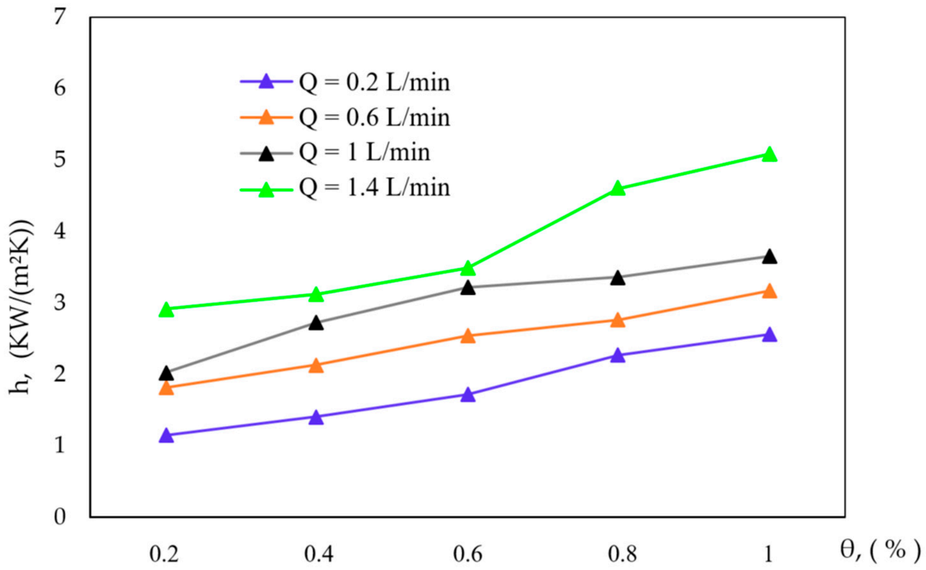

Figure 4. The impact of flow rate on the heat transfer coefficient.

3.4. The Level of Uncertainty Present

Uncertainty analysis is conducted to facilitate data analysis by employing formulas that estimate measurement errors in experimental data. In the presence of a given number N of observed data, the average, represented by the symbol x, is computed. The symbol "i" represents an integer value within the range of 1 to N. Standard deviation (SD) is a statistical measure employed to ascertain the proximity of data points in a statistical sample to the mean value of the dataset [13,14]. Table 1 presents the average water uncertainty analysis, while Table 2 displays the uncertainty analysis of average particle fraction.

Table 1. Average water uncertainty analysis.

Parameter	Average Uncertainty
Heat transfer coefficient (Q = 0.2 lpm)	±0.030
Heat transfer coefficient (Q = 0.6 lpm)	±0.017
Heat transfer coefficient (Q = 1 lpm)	±0.017
Heat transfer coefficient (Q = 1.4 lpm)	±0.026

Table 2. Uncertainty analysis of average particle fraction.

Parameter	Average Uncertainty
Heat transfer coefficient (θ = 0.2%)	±0.029
Heat transfer coefficient (θ = 0.4%)	±0.036
Heat transfer coefficient (θ = 0.6%)	±0.038
Heat transfer coefficient (θ = 0.8%)	±0.053
Heat transfer coefficient (θ = 1%)	±0.042

4. Conclusions

The present study investigates the impact of incorporating aluminum oxide (Al_2O_3) particles into a heat exchanger, along with the manipulation of the flow rate of the Al_2O_3/water nanofluid. The obtained outcomes reveal a positive correlation between the concentration of Al_2O_3 particles and the heat transfer coefficient. Incorporating nanoparticles at concentrations of up to 1% has resulted in a notable enhancement in the heat transfer coefficient, with a maximum increase of 17.29%. Furthermore, the heat transfer coefficient exhibits a positive correlation with the flow rate of the Al_2O_3/water nanofluid. The augmentation of the heat transfer coefficient by a maximum of 29.95% can be achieved by elevating the flow rate from 0.2 to 1.4 L per minute (lpm).

Author Contributions: N. (Ngisomudin) carried out the experimental methods, A.D.A. composed the manuscript, M.E. carried out the data analysis, and N. (Ngafwan) prepared the supplies and instruments. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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