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Experimental Investigation of Nanofluid-Cooled Minichannel Heat Sinks

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ABSTRACT

Efficient thermal management is critical in high-performance electronic devices, where heat sinks play a vital role in dissipating heat. Conventional cooling fluids, such as water or ethylene glycol, are limited by low thermal conductivity. This project investigates the performance enhancement of heat sinks using nanofluids engineered colloidal suspensions of nanoparticles in base fluids due to their superior thermophysical properties. The experimental study explores Al_2O_3-water mixture, with varying concentrations and flow rates. A custom-built test rig was developed to simulate electronic heat generation and measure cooling performance under forced convection. Key parameters analyzed include thermal resistance, heat transfer coefficient, and temperature gradient across the heat sink. Results reveal that nanofluids significantly enhance heat dissipation compared to conventional fluids, with Al_2O_3-water nanofluid demonstrating up to 25% higher heat transfer coefficient. This work concludes that nanofluid-based heat sinks are a promising solution for nextgeneration electronic cooling systems, offering improved thermal management and energy efficiency.

Key Words: A Nanofluid based experiment with enhanced heat transfer rate than conventional fluid.

1. INTRODUCTION

In the present years of modernization and due to the technology advancement, the need of liquid cooling in various compact electronic devices and other electrical devices has been a major area of concern. The heat generated by electronic circuits must be dissipated out of the system so we require different cooling systems for these devices to work properly and effectively. Since the last few years minichannel cooling system has been a subject of research. The amount of work on the effect of heat transfer on flow geometries in minichannels is fast and growing. Many researchers have emerged with a different cross section of the minichannel but for sure there is an effect of the configuration of these channels on heat transfer coefficient, Nusselt number, and Reynold number. The main advantage of using minichannel is to achieve a high heat dissipation rate in a smaller space. It has been proved that single-phase, laminar flow, and forced convection in minichannels is one of the effective cooling ways in a variety of applications.

1.1 History

The minichannel heat sink was first developed and proposed by Tuckerman and Pease in 1981. For VLSI circuits, an investigation has been done by authors with a high performance heat sink. Designed and tested water cooled based silicon minichannel heat sink used for integrated circuits. They also stated that reducing the dimension to the micro scale of a liquid cooling heat sink is helping in enhancing the performance of heat transfer. The experimental investigation and numerical analysis are presented by Lee et al. To explore the validity of the classical correlations for analyzing the thermal behavior in single phase rectangular minichannels that are based on conventional sized channels. The minichannel is made up of copper and de-ionized water was used for the experiment and the Reynolds number was ranging from 300 to 3500. Numerical predictions those obtained were based upon the continuum and classical approach. Those predictions were found in an appropriate agreement with the data showing an average deviation of 5%.

II. METHODOLOGY

Fabrication of the Test rig:

1. The fabrication of a durable structural frame. This frame was constructed using galvanized iron (GI) square hollow section pipes, known for their excellent strength, corrosion resistance, and structural rigidity. These square pipes were precisely measured, cut to the required lengths, and welded together to form a robust, table-like frame that would support all components of the test rig. The table frame design not only ensures mechanical stability during operation but also provides ease of access to various components during testing and maintenance. The hollow nature of the GI pipes reduces the weight of the structure while maintaining sufficient strength to bear the load of the test setup.
2. On top of the GI frame, a transparent acrylic sheet was mounted as the main working platform. Acrylic was chosen over conventional metal sheets due to its unique advantages—it is lightweight, resistant to corrosion and chemical damage, and allows visibility through the sheet, which is helpful for inspecting the plumbing and wiring underneath. The sheet was securely drilled and fastened onto the frame using stainless steel bolts, ensuring that it remains firmly in place during the experimental process. The flat and even surface of the acrylic provides a clean and stable base for placing critical components such as the induction stove, temperature indicators, heat sink, and piping.
3. To simulate heating conditions similar to those encountered in real-world thermal management systems, an induction stove was positioned on the center of the acrylic platform. The induction stove provides a controllable and consistent heat source, eliminating the variability found in open flame or resistance heating methods.
4. Above this stove, a finely machined aluminium heat sink was placed. Aluminium was selected due to its excellent thermal conductivity, low cost, and ease of fabrication. The heat sink absorbs thermal energy from the induction stove and transfers it to the nanofluid flowing through the system, allowing researchers to analyze heat transfer efficiency under various operating conditions.
5. The heated nanofluid is transported away from the heat sink using a network of gas pipes, which are covered with resistant rubber insulation. These pipes are critical for 34 maintaining the thermal integrity of the system by reducing heat loss to the environment.
6. The rubber insulation also protects the surroundings from high-temperature surfaces, enhancing the safety of the setup.
7. The fluid then enters a coiled copper heat exchanger mounted on the side of the rig. The copper coil, due to its high thermal conductivity and large surface area, serves as a highly effective medium for dissipating heat from the nanofluid. The coiled geometry increases the residence time of the fluid and maximizes its contact with ambient air, thus improving cooling efficiency.
8. To further improve the cooling process of the copper coil, a DC motor coupled with a fan was installed adjacent to the coil. This motor-driven fan forces ambient air over the coil surface, significantly enhancing convective heat transfer. The forced air cooling helps maintain lower outlet fluid temperatures and ensures the fluid is adequately cooled before recirculation.
9. The fluid reservoir, usually made from a thermally insulated material thermocol, holds the nanofluid.
10. Inside the reservoir, a feed pump is installed to ensure continuous circulation of the nanofluid throughout the test loop. The pump is essential to maintain constant flow rate and pressure, both of which are critical for reliable experimental data.
11. In order to monitor the performance of the test rig and collect meaningful data, J-type thermocouples were integrated at key points in the system—primarily at the inlet and outlet of the heat sink, and at the cooling coil outlet.
12. These thermocouples are connected to digital temperature indicators, which display accurate real-time temperature readings, helping the operator to assess thermal gradients and temperature rise across components.
13. A flow control valve was incorporated into the pipeline to allow manual adjustment of the flow rate. This provides flexibility to vary flow conditions and observe their impact on the heat transfer characteristics of the nanofluid.
14. Finally, after assembling all components and interconnecting them with appropriate tubing and wiring, the entire system was thoroughly checked for leaks, short circuits, insulation quality, and mechanical alignment.
15. The electrical system, including the temperature indicators, DC fan motor, and induction stove, was tested for proper operation.

III. Principle & Object

Principle**:**

The project is based on the principle of enhanced heat transfer using nanofluids in minichannel heat sinks. Nanofluids—suspensions of nanoparticles in a base fluid (like water)—exhibit significantly improved thermal properties over conventional fluids. When used in minichannels, which provide a high surface area-to-volume ratio, the combined effect leads to superior convective heat transfer, lower thermal resistance, and higher heat dissipation rates.

This principle is grounded in:

- **Single-phase forced convection** in narrow geometries.
- **Improved thermophysical properties** of nanofluids (e.g., thermal conductivity and specific heat).

- Use of **compact, efficient structures** (minichannels) to manage high heat fluxes in limited spaces.

Objective**:**

The objective **of the project is:**

To experimentally investigate the **thermal performance enhancement** of a heat sink using **Al_2O_3-water nanofluids** under varying flow conditions. The study aims to:

- Develop a **custom test rig** for heat transfer analysis.
- Analyze **thermal resistance, heat transfer coefficient**, and **temperature gradients** in the system.
- Compare performance with **conventional water-based cooling.**
- Determine the **effectiveness** of nanofluids in improving **electronic cooling efficiency.**

IV. LITERATURE REVIEW

1. The concept of the minichannel heat sink was first introduced by Tuckerman and Pease in 1981 [1], who proposed a high-performance, water-cooled silicon minichannel heat sink for Very Large Scale Integration (VLSI) circuits. Their study emphasized that scaling down the dimensions of heat sinks to the microscale significantly enhances heat transfer performance (D. B. Tuckerman and R. F. W. Pease., 1981).
2. Building upon this foundation, Lee et al. [2] conducted experimental and numerical investigations to assess the applicability of classical correlations in analyzing single-phase heat transfer in rectangular minichannels. Using copper minichannels with deionized water as the working fluid and Reynolds numbers ranging from 300 to 3500, their continuum-based numerical predictions showed a strong agreement with experimental results, with an average deviation of only 5% (P. S. Lee, S. V. Garimella, and D. Liu., 2005).
3. Further exploration was carried out by Qu and Mudawar [3], who studied heat transfer and pressure drop characteristics in oxygen-free copper minichannels using deionized water. Their investigation covered two rectangular channel sizes (hydraulic diameters of 231 µm and 713 µm) and various geometric configurations (rectangular, trapezoidal, and triangular). Results revealed that, under constant Reynolds numbers, increasing heat flux led to a decrease in pressure drop from the heat sink's top plate. Among different channel configurations, zigzag-shaped minichannels with equal cross-sectional areas exhibited the highest heat transfer coefficient (W. Qu and I. Mudawar., 2002).
4. Ghazali-Mohd et al. [4] compared circular and square minichannel geometries using ammonia as a coolant. Their optimization study using a genetic algorithm showed that circular channels exhibited lower thermal resistance—by 21% and 35% at low and high pumping powers, respectively—indicating superior thermal and hydrodynamic performance (S. Ghazali-Mohd et al., 2013).
5. In a related study, Chai and Tassou [5] examined the impact of cross-sectional geometry on the heat transfer and pressure drop characteristics of supercritical CO_2 in minichannels. Among six geometries (square, semicircle, circle, equilateral triangle, ellipse, and rectangle) with equal hydraulic diameter (1.22 mm), circular and elliptical channels yielded the highest heat transfer coefficients (L. Chai and S. A. Tassou., 2015).
6. Ghasemi et al. [6] experimentally investigated thermal performance and hydraulic parameters of aluminum heat sinks with four circular minichannels, varying in hydraulic diameters. Their findings indicated that smaller diameters (4 mm) offered lower thermal resistance than larger ones (6 mm and 8 mm) (M. Ghasemi et al., 2014).
7. Kewalramani et al. [7] developed an empirical correlation for laminar forced convection in trapezoidal minichannels. Their study included both experimental and numerical analyses, focusing on aspect ratios from 0.1 to 10 and side angles of 30° and 60°, to evaluate the Poiseuille and Nusselt numbers (M. A. Kewalramani et al., 2016).
8. Su et al. conducted a numerical investigation on elliptical minichannels and proposed a general correlation for apparent friction coefficients and entrance length, taking into account Reynolds number and aspect ratio effects. Moghanlou et al. [8] carried out an experimental study on square minichannels with bottom-mounted heaters. With Reynolds numbers ranging from 14 to 450, the study reported accuracies of 17% for thermal resistance, 8% for the Nusselt number, and 14% for the friction factor (F. S. Moghanlou et al., 2016).

V. Required Materials & purpose

1. **GI Square Hollow Section Pipe (for Frame)**
   - Used to fabricate the structural frame of the test rig.
   - Provides mechanical support, corrosion resistance, and rigidity for mounting components.
2. **Acrylic Sheet**
   - Serves as the top platform for mounting components like the heat sink and sensors.

- Offers transparency for visual inspection and is thermally and electrically insulating.

3. **Induction Stove**
   - Acts as the heat source to simulate real-world thermal loads.
   - Provides precise, flame-free heating directly to the aluminum heat sink.
4. **Aluminum Heat Sink**
   - The core component for absorbing and dissipating heat.
   - Contains mini-channels to improve heat transfer to the circulating nanofluid.
5. **Gas Pipes with Rubber Insulation**
   - Used to transport the nanofluid between components.
   - Rubber insulation helps in minimizing heat loss and maintaining temperature accuracy.
6. **Copper Coil**
   - Functions as a cooling coil for the hot nanofluid.
   - High thermal conductivity of copper ensures efficient cooling via increased surface area.
7. **J-Type Thermocouples**
   - Measure temperature at various points (inlet, outlet, etc.).
   - Provide real-time monitoring of temperature changes during the experiment.
8. **Digital Temperature Indicators**
   - Display the temperature readings from thermocouples.
   - Help in monitoring thermal performance and recording data.
9. **Feed Pump**
   - Maintains continuous circulation of nanofluid throughout the test loop.
   - Ensures stable flow rate and helps achieve desired Reynolds numbers.
10. **Flow Control Valve**
    - Allows for manual regulation of the fluid flow rate.
    - Used to analyze performance under different flow conditions (laminar to turbulent).
11. **DC Motor with Fan**
    - Mounted near the copper coil to provide forced air cooling.
    - Enhances convection and helps lower the temperature of returning nanofluid.

VI. WORKING OF THE PROPOSED SYSTEM:

The experimental setup operates by simulating a real-world electronic cooling scenario, where heat is generated and needs to be effectively dissipated. The core of the test rig is built on a sturdy frame made from GI square hollow section pipes, with an acrylic sheet serving as the platform for mounting the primary components. At the heart of the system lies an aluminum mini-channel heat sink placed directly above an induction stove. The induction stove functions as a clean and controllable heat source, heating the aluminum base and mimicking the thermal load typically experienced in electronic devices. When the stove is activated, it heats the aluminum block, and this heat is transferred to the nanofluid flowing through the mini-channels embedded in the heat sink.

A centrifugal feed pump draws the nanofluid—an Al_2O_3-water mixture—from a thermally insulated reservoir and pushes it through insulated gas pipes into the mini-channels. As the nanofluid flows through the heat sink, it absorbs the heat from the aluminum surface due to its superior thermal conductivity. This results in a reduction of the heat sink's surface temperature and demonstrates the enhanced cooling capability of the nanofluid compared to regular water. After passing through the heat sink, the heated nanofluid enters a copper cooling coil mounted on the side of the frame. A DC fan is installed adjacent to the coil, which forces ambient air over the coil to enhance the convective heat transfer, effectively cooling the fluid before it returns to the reservoir for recirculation.

To monitor and control the thermal performance, J-type thermocouples are strategically placed at the inlet and outlet of the heat sink and on its surface. These sensors provide real-time temperature readings via digital indicators. A flow control valve is also integrated into the pipeline to adjust the fluid flow rate, allowing the investigation of various flow regimes, including laminar and transitional flows. This entire setup enables the evaluation of heat transfer efficiency by comparing temperature drops across the system under different nanofluid concentrations and flow rates, highlighting the effectiveness of nanofluids in thermal management applications.

VII. RESULT

Numerical Analysis

1) The average heat transfer coefficient:

$$\propto_{ave} = \frac{q}{T_{w,ave} - T_f}$$

Where:

$T_{w,ave}$ – Average Surface Temperature

T_f – Average Fluid Temp

$$T_f = \frac{T_{f\,in} + T_{f\,out}}{2}$$

2) Heat Flux:

$$q = \frac{Q}{A_t}$$

$$A_t = A_p + \eta_f A_s$$

Where:

A_p – Area of primary heat transfer

A_s – Secondary area of heat transfer

3) Efficiency of fin:

$$\eta_f = \frac{th(mH)}{mH}, mH = \sqrt{\frac{\alpha p}{\lambda_w A_c}}$$

Where:

η_f – Efficiency of fin

mH – Heat transfer coefficient $\propto$

λ_w – Thermal conductivity of the channel

4) $q = -\lambda_w \frac{dT_w}{dx}$

$$T_w = T_f + \frac{T_{up,in} - T_f}{\cosh(mH)}$$

Where:

T_w & $T_{up,in}$ are the local wall temp at bottom and upper surface

5) $Re = \frac{\rho_f u D_h}{\mu_f}$

6) $Nu = \frac{\alpha D_h}{\lambda_f}$

Where:

ρ_f – Density of fluid

μ_f – Dynamic viscosity of fluid

λ_f – Thermal conductivity of fluid

7) $Re = \frac{\rho_n u_{in} D_h}{\mu_n}$

Where:

ρ_n – Density of Nanofluid

u_{in} – Dynamic viscosity

D_h - Hydraulic dia

8) $D_h = \frac{2W_{ch}H_{ch}}{(W_{ch}+H_{ch})}$

9) $f = \frac{\Delta_p D_h}{2\rho_n u_{in}^2 L_{ch}}$

10) $Nu = \frac{qL_{ch}W_s D_h}{A_{if}(T_b - T_{n,avg})k_n}$

$T_{n,avg} = \frac{T_{in}+T_{out}}{2}$

Where:

Δ_p – Pressure drop

W_s – Width of solid domain

A_{if} – Area of the interface between solid and fluid domains

T_b – Avg temp of bottom surface

Experimental Analysis

The experimental study was conducted on the fabricated nanofluid-based heat sink test rig under controlled conditions. The system was tested using both distilled water and a nanofluid (Al_2O_3-water) at various flow rates and heat inputs. Temperature readings were recorded at the inlet and outlet of the heat sink using J-type thermocouples, and real-time data was displayed using digital temperature indicators.

Result

The experimental study was conducted on the fabricated nanofluid-based heat sink test rig under controlled conditions. The system was tested using both distilled water and a nanofluid (Al_2O_3-water) at various flow rates and heat inputs. Temperature readings were recorded at the inlet and outlet of the heat sink using J-type thermocouples, and real-time data was displayed using digital temperature indicators.

Observations:

Table 4.1 Observations

S. No	**Nanofluid Concentration**	**Inlet Temp (°C)**	**Outlet Temp (°C)**	**Heat Sink Surface Temp (°C)**
1	Water (0%)	27	38	72
3	0.3% Al_2O_3	27	35	66
5	0.5% Al_2O_3	27	33	60
7	0.7% Al_2O_3	27	32	58

Graphical Representation:

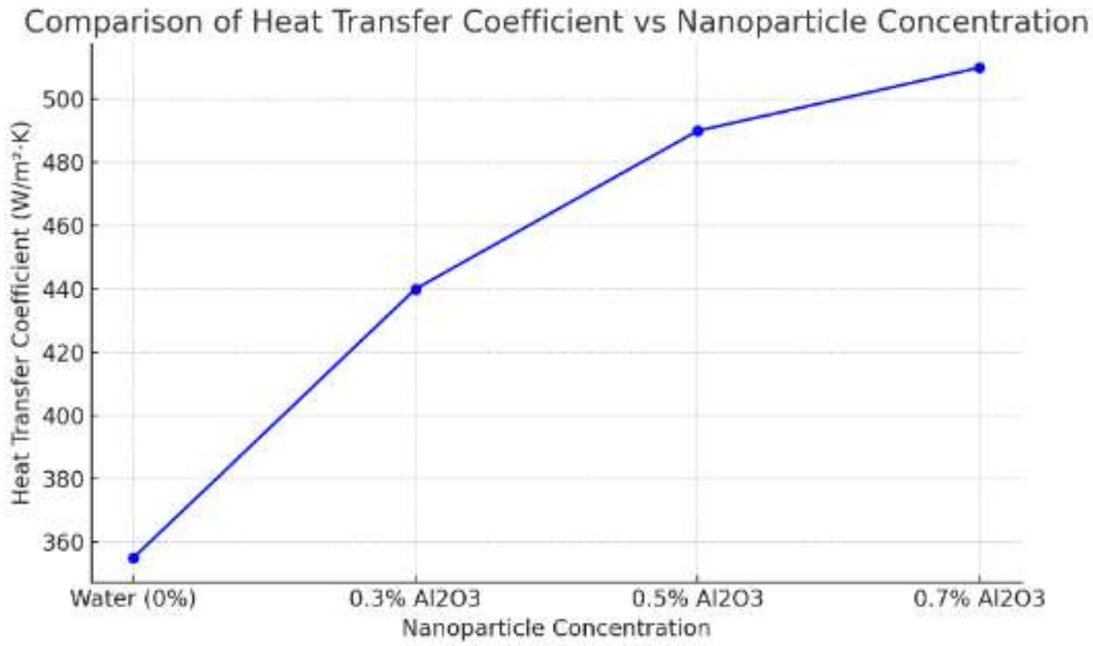

Fig.4.1 Graphical representation of recorded data

VIII. CONCLUSION

The developed nanofluid-based heat sink test rig successfully demonstrated the enhanced thermal performance of nanofluids compared to conventional fluids. The integration of components such as an aluminium heat sink, induction heater, copper coil, and thermocouples in a well-structured GI frame allowed for efficient experimentation and observation. Results showed that nanofluids provide significantly better heat dissipation due to their improved thermal properties.

This study confirms that nanofluids are promising candidates for next-generation cooling systems. They offer better heat transfer rates, reduced thermal gradients, and improved energy efficiency, especially in compact and high-heat-load systems. The rig also provides a flexible platform for further research, such as testing different nanofluid types, concentrations, and flow configurations. Future work can focus on long-term stability of nanofluids, cost-effectiveness, and integration with renewable energy systems for sustainable cooling solutions.

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