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Enhancing Heat Transfer in Micro-Channel Heat Sinks through Geometrical Optimization

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Abstract

This study experimentally investigates the influence of micro-channel height and width on heat transfer and pressure drop within heat sinks, aiming to optimize their geometry for enhanced thermal performance and minimized pressure loss. Varying flow rates and heat fluxes were applied to different channel configurations to determine the heat transfer coefficient and Nusselt number. Results show that narrower (0.3 mm vs. 0.4 mm) and taller (2.0 mm vs. 1.5 mm) channels improved heat transfer due to increased surface area, but also increased pressure drop. Higher Reynolds numbers (400-1200) and heat flux (2.0-6.5 kW/m^2) enhanced heat transfer, especially in narrower channels, while surface roughness further improved thermal performance at the expense of higher flow resistance. Optimized geometries effectively reduced heat sink temperature. This research provides valuable insights for designing efficient micro-channel heat exchangers for high-power electronics by balancing thermal and hydraulic performance.

Major Findings: *Micro-channel heat sinks demonstrate a significant enhancement in heat transfer when the channel surfaces exhibit roughness. However, this improved heat transfer performance comes at the cost of increased pressure drop within the system. To effectively utilize micro-channel cooling systems, careful optimization of channel geometry is essential to strike a balance between maximizing heat transfer and minimizing the associated pressure drop.*

Keywords: *Channel Geometry, Heat Flux, Heat Sink, Heat Transfer, Micro-Channel, Nusselt Number, Pressure Drop, Reynolds Number*

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1.0 Introduction

The rising demand for compact and high-performance cooling systems in electronic devices has driven significant interest in micro-channel heat sinks as an effective thermal management solution. These devices offer the advantage of high surface area-to-volume ratios, enabling efficient heat dissipation in compact spaces. However, the performance of micro-channel heat sinks is heavily influenced by their geometric parameters, such as channel height and width. Understanding the interplay between these dimensions and their impact on heat transfer and pressure drop is critical for optimizing the design and operation of micro-channel heat exchangers. This study delves into the effects of channel height and width on the thermal and hydraulic performance of micro-channel heat sinks to advance the knowledge base in this domain.

To systematically assess these effects, a series of experiments were conducted across various flow rates and heat flux conditions. The study quantified key thermal and hydraulic parameters, including the heat transfer coefficient and Nusselt number, for multiple configurations of channel geometries. These parameters are widely recognized as essential indicators of heat transfer efficiency and flow resistance in heat exchangers. By exploring a range of configurations, the study provides a comprehensive understanding of how variations in channel dimensions affect both heat dissipation and pressure drop. This experimental approach ensures that the findings are grounded in real-world performance, offering practical insights for the design of micro-channel systems.

Previous research by Kurhade *et al.*[1-6], Waware *et al.*[7-9], and Khot *et al.*[10-14] has explored various methods to enhance heat transfer, including material selection, CFD analysis, and the use of twisted tape inserts. Luo *et al.*[15] investigated combined effects of air bubble injection, Perforated Wavy Strip Turbulators (PWST), and nanofluids in a double pipe heat exchanger, achieving significant increase in heat transfer. Kumar *et al.*[16] studied the performance of a heat exchanger tube with a novel perforated conical ring and twisted tape inserts. Other researchers, such as Aldawi[17], Ahmad *et al.*[18], and Afanasyev *et al.*[19], have explored the impact of twisted tapes, corrugated geometries, and spherical cavities on heat transfer and friction. Bunker *et al.*[20] explained Heat transfer and friction factors for flows inside circular tubes with concavity surface. Chyu *et al.*[21] found that concave dimpled surfaces can significantly enhance heat transfer compared to smooth surfaces, with pressure losses significantly lower than those caused by ribbed turbulators. Isaev *et al.*[22] demonstrated that transforming the separation flow structure can further improve heat transfer. Ligrani *et al.*[23], Moon *et al.*[24], Mahmood *et al.*[25], and Syred *et al.*[26] have conducted studies on the [flow structure, heat transfer, and hydrodynamics] in dimpled channels. Mohadjer *et al.*[27] compared the performance of different turbulators and found that while some turbulators can improve heat transfer, others may have a [negative impact]. Abed *et al.*[28] investigated the use of bubble injection and magnetic turbulators to enhance heat transfer. Kumar *et al.*[29] evaluated the efficiency of a solar thermal air collector with discrete multi-arcshaped ribs. Kurhade *et al.*[30-32] explain the performance of solar collectors and the use of biodiesel and dimethyl carbonate blends on engine performance. Waware *et al.*[33] did a review on a [comprehensive evaluation] of recent studies investigating nanofluids utilization in heat exchangers. Kurhade *et al.*[34-39] explained experimental studies on MQL grinding and heat transfer in electronic components revealed the influence of substrate board thermal conductivity and PCM placement on temperature regulation. Numerical and experimental investigations explored heat transfer from IC chips mounted on SMPS boards, while a comprehensive review analyzed electronic cooling technologies in harsh environments. Aerofoil design optimization through CFD simulations and wind tunnel experiments, combined with fuzzy logic techniques for predicting heat transfer enhancement using twisted tape inserts, provided insights into heat exchanger efficiency. Researchers delve into a range of topics, including the mechanical behavior of curved plates[40,41], the thermal performance of electronic components[42], heat transfer enhancement techniques like twisted tape inserts[43,44] and the development of advanced cooling solutions for electronics in challenging environments[45] and CFD-based optimization for heat exchangers[46,49].

The results reveal that channel geometry plays a pivotal role in determining the overall performance of micro-channel heat sinks. Variations in channel height and width were found to significantly impact the heat transfer characteristics and pressure drop, underscoring

the need for careful consideration of these factors during the design phase. These findings have broad implications for improving the thermal management of high-power electronic devices, where efficient heat removal is crucial to maintaining performance and reliability. By providing actionable data and insights, this study contributes to the development of next-generation micro-channel heat exchangers that meet the demands of modern electronic systems.This study builds on prior research by systematically investigating the effects of channel height, channel width, Reynolds number (400–1200), and heat flux (2.0–6.5 kW/m²) on heat transfer coefficient and Nusselt number. The findings aim to provide insights for optimizing MCHS designs to address the cooling requirements of advanced electronics with high heat dissipation, contributing to more efficient thermal management solutions.

2.0 Experimental Setup and Procedure

The experimental setup, as shown in Figures 1 and 2, comprised a blower unit linked to a test tube. A nichrome heater was coiled around the test section to supply heat.

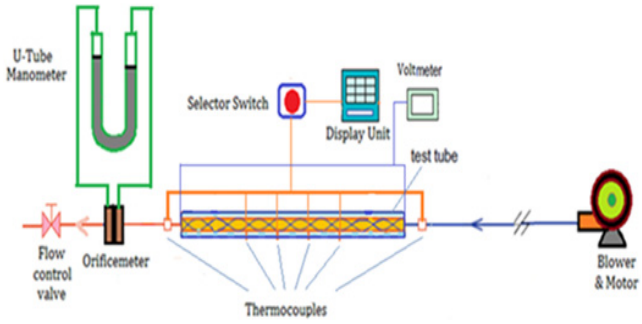


Figure 1. Schematic diagram.

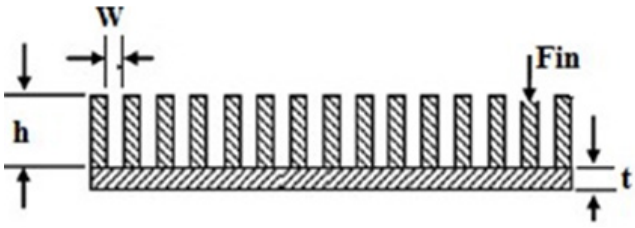


Figure 2. Test section.

Four thermocouples were embedded in the test section's wall to record its temperature, while two additional thermocouples were positioned in the air stream at the inlet and outlet to monitor air temperatures. The test tube was connected to the blower outlet, and an orifice meter was installed to measure air flow rates. A power unit supplied electricity to the heater, and power consumption was measured using meters. It's crucial to note that only a portion of the total supplied heat was used to heat the air. An orifice meter and a water manometer were employed to measure air flow rates. A valve at the pipe outl*et a*llowed for adjusting the air flow rate. A tapping with a valve was provided at the test section's inlet to measure pressure drop.

3.0 Result and Discussion

Figure 3 shows how outlet air temperature changes with different air flow rates for various channel widths. As the air flow increases, so does the heat transfer, but not as proportionally. This leads to a decrease in outlet air temperature with higher flow rates. Wider channels, with their larger surface area and potentially rougher surfaces, transfer heat less efficiently. This explains why narrower channels (like w=0.3 mm) have higher outlet air temperatures compared to wider ones (like w=0.4 mm).

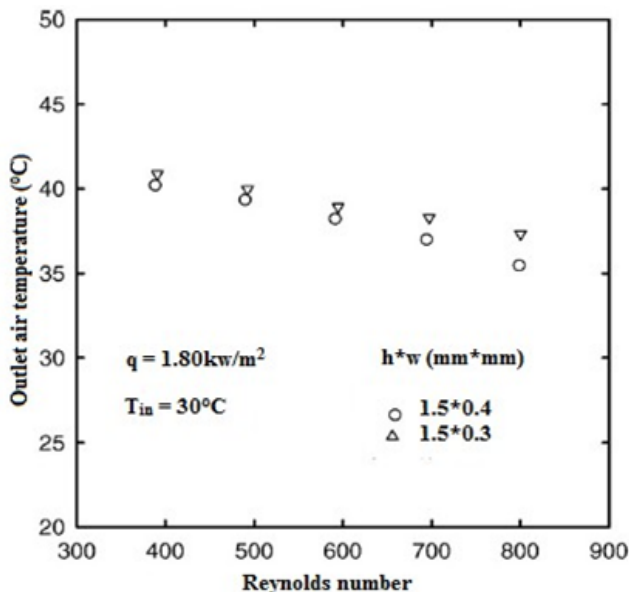


Figure 3. Outlet air temperature vs Reynolds number.

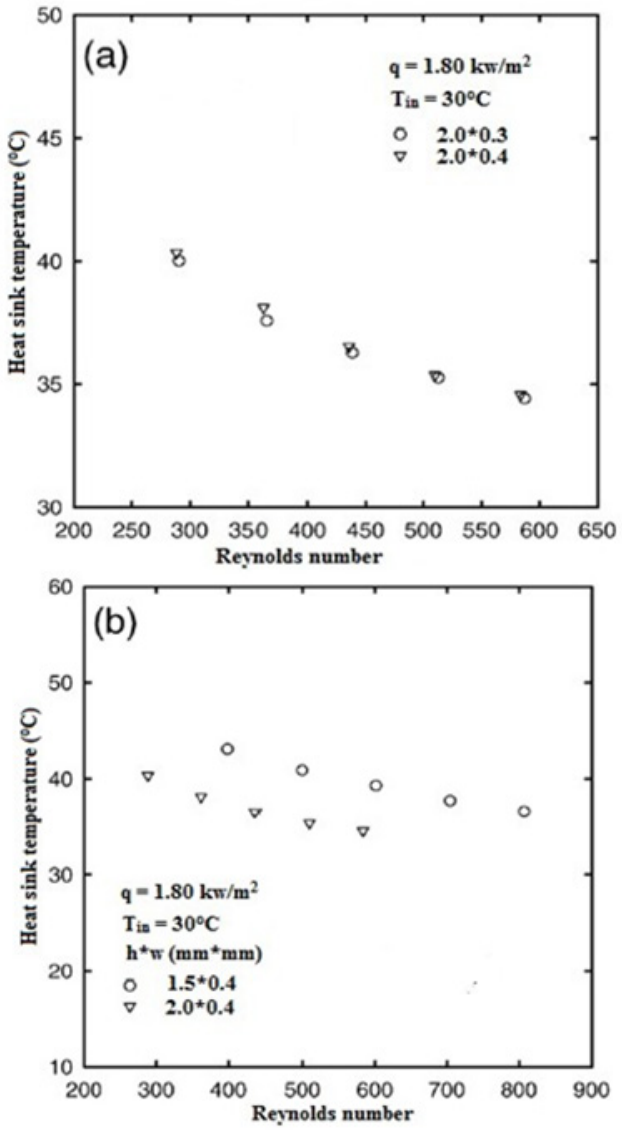


Figure 4. Heat sink temp vs with air Reynolds number for (a) Widths (b) Heights.

Figure 4 illustrates the relationship between average heat sink temperature and air flow rate for different channel dimensions. As expected, higher air flow rates lead to lower heat sink temperatures, indicating improved cooling. Similar to the trend in Figure 3, narrower channels have lower average heat sink temperatures due to their larger surface area. However, this effect is less pronounced for the small differences in channel width considered here. Additionally, taller channels generally exhibit lower average heat sink temperatures compared to shorter ones.

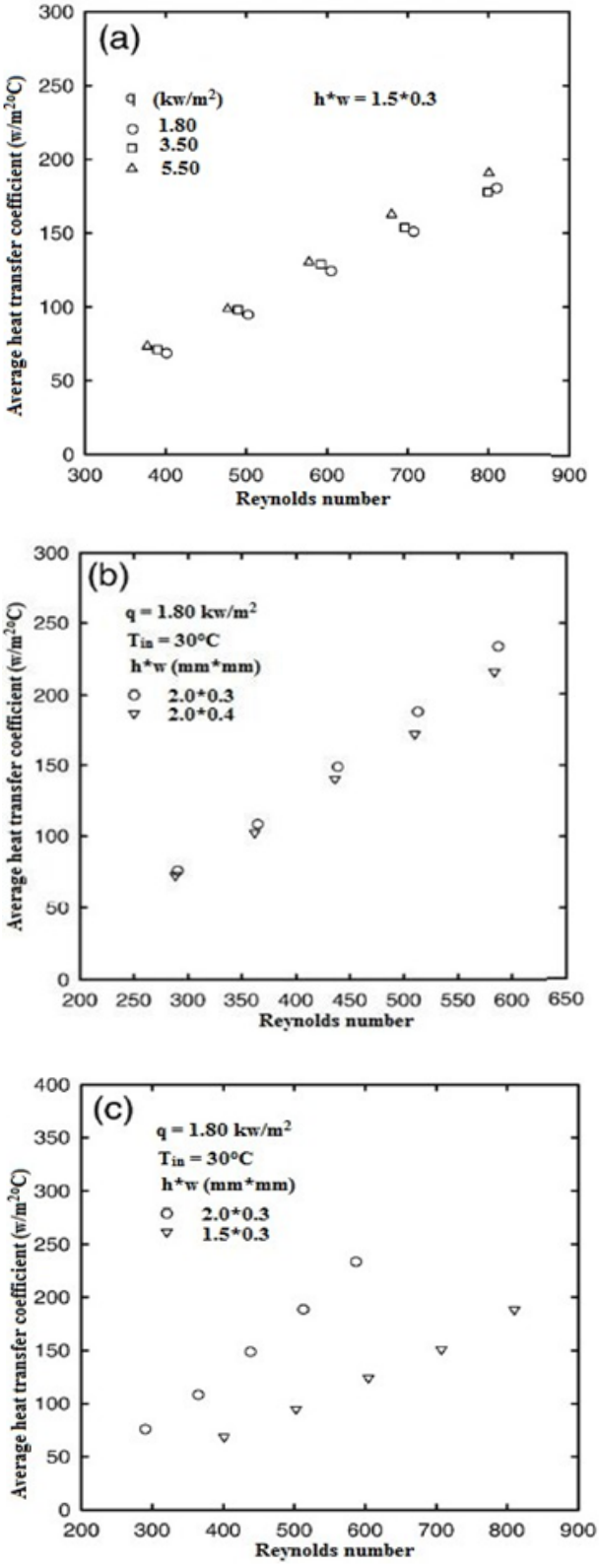


Figure 5. Heat transfer coefficient vs Reynolds number for (a) Heat fluxes (b) Widths (c) Heights.

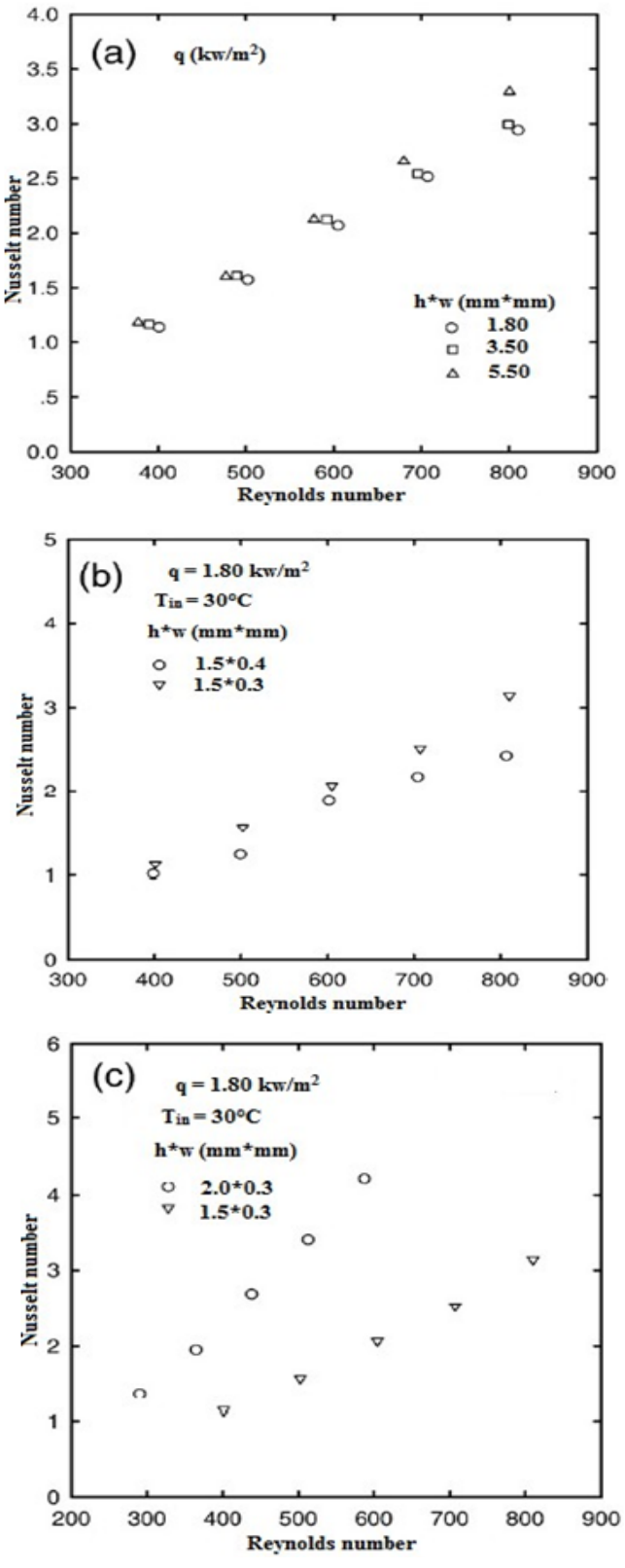


Figure 6. Nusselt number Vs Reynolds number for (a) Heat fluxes (b) Widths (c) Heights.

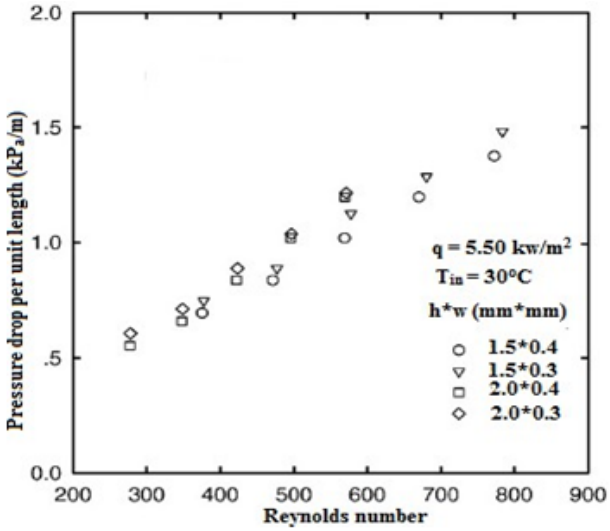


Figure 7. Pressure drop vs Reynolds number.

Figure 4. Figure 5 shows how the heat transfer coefficient changes with air flow rate and heat flux. As expected, higher heat fluxes lead to higher heat transfer coefficients due to increased temperature differences. For a given air flow rate, narrower channels (w=0.3 mm) exhibit higher heat transfer coefficients compared to wider channels (w=0.4 mm). This is because narrower channels have a larger surface area available for heat transfer.

Taller heat sinks (h=2.0 mm) generally have higher heat transfer coefficients than shorter ones (h=1.5 mm) due to their larger surface area and potentially rougher surface. This trend is consistent across different presentations of the data, as shown in Figure 6.

Figure 7 shows how pressure drop varies with different channel dimensions. Micro-channel flows are more complex than conventional flows due to increased surface forces and roughness. While conventional tube roughness can be estimated, more research is needed to accurately determine roughness in micro-channels.

4.0 Conclusion

As electronic devices become smaller and more powerful, micro-channel cooling systems are gaining importance. However, the performance of these systems, especially in terms of heat transfer and pressure drop, is still not fully understood. This research experimentally investigates the impact of different channel geometries on heat transfer and pressure drop-in micro-channel heat sinks. The

results show that the roughness of the channel surface plays a significant role in enhancing heat transfer while also increasing pressure drop.

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