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CFD Analysis of Heat Transfer Enhancement in Microchannel Heat Sinks

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ABSTRACT

The rapid advancement of electronic devices, high-performance computing systems, and compact thermal management technologies has increased the demand for efficient heat dissipation solutions. Microchannel heat sinks have emerged as promising cooling technologies due to their high surface-area-to-volume ratio, compact structure, and superior heat transfer capabilities. This study focuses on the Computational Fluid Dynamics (CFD) analysis of heat transfer enhancement in microchannel heat sinks by investigating the influence of different geometrical configurations, flow characteristics, and operating parameters on thermal and hydraulic performance. Numerical simulations are proposed to examine the effects of channel dimensions, channel shapes, inlet velocity, coolant properties, and applied heat flux on temperature distribution, pressure drop, heat transfer coefficient, and overall thermal resistance.

Different enhancement techniques, including ribbed surfaces, wavy channels, pin-fin structures, and optimized channel geometries, are considered to improve heat transfer performance. The governing equations of continuity, momentum, and energy are solved using appropriate CFD models under steady-state flow conditions. The numerical results are evaluated through important performance indicators, such as Nusselt number, Reynolds number, friction factor, and pressure drop. The study aims to identify an optimal microchannel configuration that provides maximum heat removal with minimum pumping power requirements. The expected findings may contribute to the development of advanced cooling systems for electronic components, microprocessors, power electronics, and other high-heat-flux applications. Overall, this research highlights the importance of CFD-based numerical modelling in designing energy-efficient, compact, and thermally optimized microchannel heat sinks for next-generation thermal management applications.

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INTRODUCTION

The increasing demand for high-performance electronic devices, advanced computing systems, power electronics, and compact thermal management solutions has created significant challenges in effective heat dissipation. Modern electronic components generate considerable amounts of heat within increasingly smaller spaces, making conventional cooling techniques less effective. Excessive heat generation can reduce device performance, decrease operational efficiency, shorten component lifespan, and cause thermal failures. Therefore, the development of efficient cooling technologies has become an important area of research in thermal engineering. Among various cooling techniques, microchannel heat sinks have attracted considerable attention because of their ability to remove large amounts of heat from compact surfaces.

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Microchannel heat sinks are advanced thermal management devices consisting of small-scale channels through which a cooling fluid flows to absorb and transport heat. Their high surface-area-to-volume ratio, compact dimensions, and enhanced heat transfer characteristics make them suitable for applications involving high heat flux. These systems are widely investigated for cooling microprocessors, semiconductor devices, laser systems, electric vehicle power electronics, and high-density electronic circuits. The thermal performance of microchannel heat sinks depends on several parameters, including channel geometry, hydraulic diameter, channel height, channel width, coolant velocity, fluid properties, and applied heat flux.

Computational Fluid Dynamics (CFD) has become an essential numerical tool for investigating fluid flow and heat transfer characteristics in microchannel heat sinks. CFD simulations provide detailed information about temperature distribution, velocity profiles, pressure variations, turbulent or laminar flow characteristics, and heat transfer coefficients. By solving the governing equations of mass, momentum, and energy conservation, CFD models help researchers understand the complex interactions between fluid flow and thermal transport within microchannels. Numerical analysis also reduces the need for expensive experimental investigations during the initial stages of heat sink design and optimization.

THEORETICAL FRAMEWORK

Fundamental Principles of Microchannel Heat Transfer

Microchannel heat sinks operate on the principles of forced convection heat transfer, in which a cooling fluid passes through small channels and absorbs thermal energy from a heated surface. Their effectiveness is primarily attributed to their high surface-area-to-volume ratio, which enables substantial heat transfer within a relatively small physical space. The thermal performance depends on fluid flow characteristics, channel dimensions, material properties, and operating conditions.

Heat transfer in microchannels generally occurs through three mechanisms:

- Conduction: Thermal energy transfers through the solid material of the heat sink.
- Convection: Heat transfers between the heated channel walls and the flowing coolant.
- Fluid mixing: Fluid motion and mixing influence the temperature distribution and thermal boundary layer development.

The combined effects of these mechanisms determine the overall cooling performance of the microchannel heat sink.

2. Governing Equations of CFD Analysis

Computational Fluid Dynamics is based on mathematical equations describing the conservation of mass, momentum, and energy. These equations are essential for predicting fluid flow and thermal behavior within microchannel structures.

2.1 Continuity Equation

The continuity equation represents the conservation of mass within the fluid domain.
For incompressible, steady-state flow:

$$\nabla \cdot \vec{V} = 0$$

Where:

- $\vec{V}$ = Fluid velocity vector.
- ∇ = Del operator.

2.2 Momentum Equation

The momentum equation describes the relationship between fluid velocity, pressure, and viscous forces.

$$\rho(\vec{V} \cdot \nabla)\vec{V} = -\nabla P + \mu \nabla^2 \vec{V}$$

Where:

- ρ = Fluid density.
- P = Fluid pressure.
- μ = Dynamic viscosity.
- $\vec{V}$ = Fluid velocity.

This equation helps determine the velocity distribution and pressure drop inside microchannels.

2.3 Energy Equation
The energy equation describes thermal energy transport through conduction and convection.
For steady incompressible flow with constant properties and negligible viscous dissipation:

$$\rho C_p(\vec{V} \cdot \nabla T) = k\nabla^2 T$$

Where:

- C_p = Specific heat capacity.
- T = Temperature.
- k = Thermal conductivity.

This equation is used to predict temperature distribution and heat transfer characteristics within the microchannel heat sink.

3. Reynolds Number and Flow Characteristics
The Reynolds number is a dimensionless parameter used to characterize fluid flow conditions and determine whether the flow is laminar or turbulent.

$$Re = \frac{\rho V D_h}{\mu}$$

Where:

- V = Average fluid velocity.
- D_h = Hydraulic diameter.
- ρ = Fluid density.
- μ = Dynamic viscosity.

The hydraulic diameter of a rectangular microchannel is expressed as:

$$D_h = \frac{2WH}{W + H}$$

Where:

- W = Channel width.
- H = Channel height.

In microchannel heat sinks, laminar flow is frequently encountered because of small hydraulic diameters and relatively low flow velocities. However, flow conditions depend on geometry and operating parameters.

4. Heat Transfer Coefficient and Nusselt Number
The heat transfer coefficient indicates the ability of the cooling fluid to absorb thermal energy from the heated channel walls.

$$Q = hA(T_w - T_f)$$

Where:

- Q = Heat transfer rate.
- h = Convective heat transfer coefficient.
- A = Heat transfer surface area.
- T_w = Average wall temperature.
- T_f = Representative bulk fluid temperature.

The Nusselt number represents the relative contribution of convective heat transfer compared with conductive heat transfer.

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$$Nu = \frac{hD_h}{k_f}$$

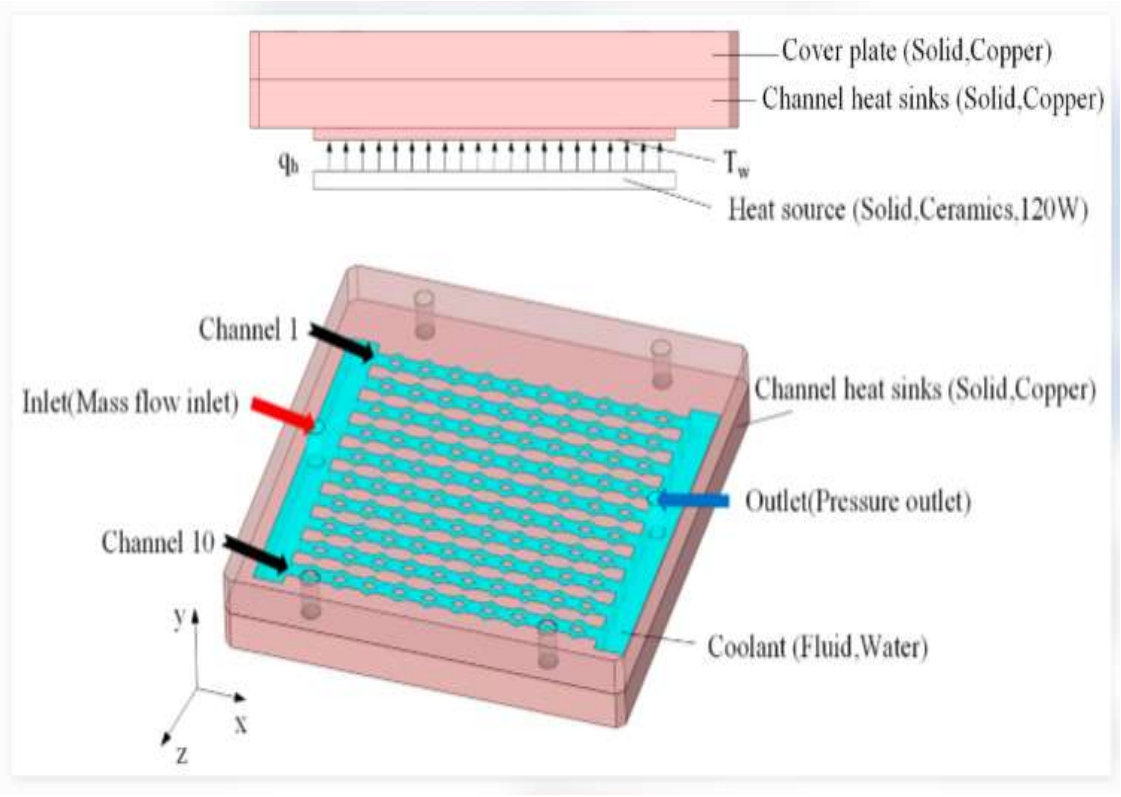
Where k/f represents the thermal conductivity of the cooling fluid.
A higher Nusselt number generally indicates improved convective heat transfer performance.

PROPOSED MODELS AND METHODOLOGIES

1. Proposed Research Model

The proposed research focuses on developing and evaluating an optimized microchannel heat sink using Computational Fluid Dynamics (CFD) to enhance heat transfer performance while minimizing pressure drop and pumping power. The numerical investigation considers different channel geometries, coolant flow conditions, and thermal boundary conditions to identify the most effective cooling configuration.

The proposed model integrates fluid flow analysis, heat transfer modelling, and thermohydraulic performance evaluation. Four different microchannel configurations—rectangular, wavy, ribbed, and pin-fin—are considered for comparative investigation.



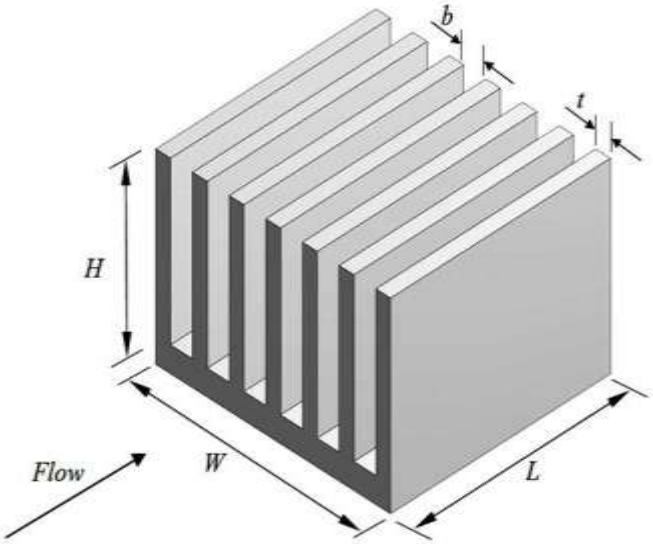
2. Geometrical Modelling of Microchannel Heat Sinks

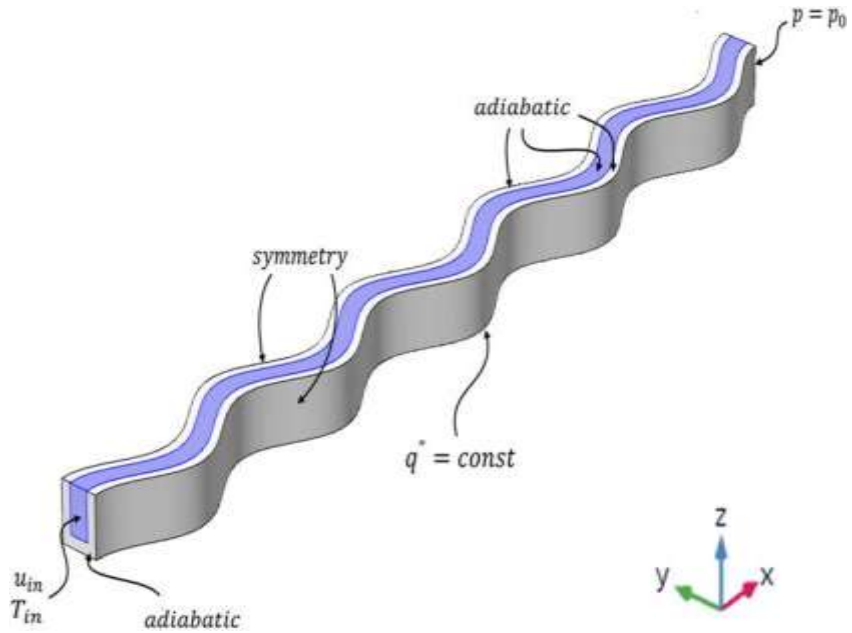
The first stage involves developing three-dimensional geometrical models of microchannel heat sinks using CAD software such as ANSYS SpaceClaim, SolidWorks, or DesignModeler.

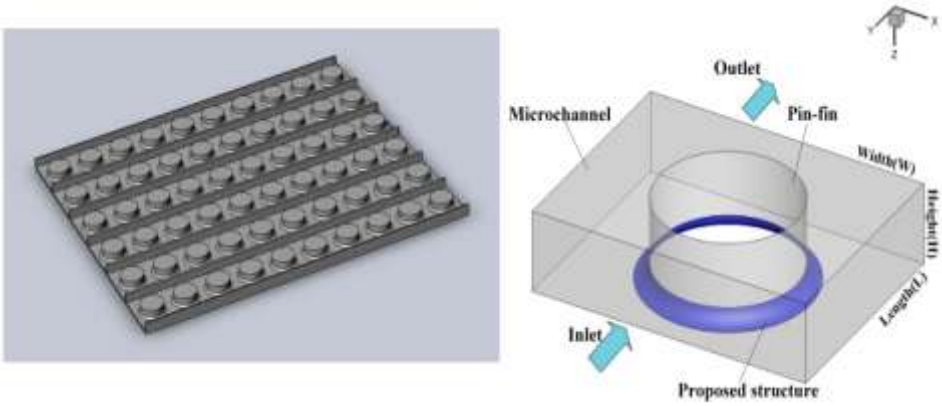
The proposed configurations include:

- Model 1: Rectangular Microchannel: A conventional straight-channel arrangement used as the reference model.
- Model 2: Wavy Microchannel: A modified channel geometry designed to improve fluid mixing and thermal boundary layer disruption.
- Model 3: Ribbed Microchannel: Incorporates ribs on channel walls to increase heat transfer surface interaction.
- Model 4: Pin-Fin Microchannel: Uses small pin-shaped structures to increase effective heat transfer area and modify fluid flow patterns.

The dimensions of the heat sink, channel width, channel height, channel length, and spacing between adjacent channels are maintained consistently wherever possible to ensure a meaningful comparison.


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W
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symmetry
q˙ = const
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Tin
adiabatic


Outlet
Microchannel
Pin-fin
Inlet
Proposed structure
(a)
(b)


smooth pin-fin
filleted pin-fin
bulbed pin-fin

(c)

3. Material Selection and Coolant Properties

Material selection significantly influences the thermal conductivity and overall heat dissipation capability of microchannel heat sinks.

The proposed study considers copper and aluminium as potential heat sink materials because of their favorable thermal properties.

Material	Thermal Conductivity (Approx.)	Application
Copper	385–400 W/m·K	High-performance cooling
Aluminium	200–237 W/m·K	Lightweight thermal systems
Silicon	120–150 W/m·K	Microelectronic cooling

Water is selected as the primary working fluid because of its high specific heat capacity, availability, and favorablethermal characteristics. Additional coolant configurations, such as water-based nanofluids, may be investigated as an extended research component.

4. Mathematical and Numerical Modelling

The numerical investigation is based on the conservation equations of mass, momentum, and energy.

4.1 Continuity Equation

$$\nabla \cdot (\rho \vec{V}) = 0$$

4.2 Momentum Equation

$$\rho(\vec{V} \cdot \nabla)\vec{V} = -\nabla P + \mu \nabla^2 \vec{V}$$

4.3 Energy Equation

$$\rho C_p(\vec{V} \cdot \nabla T) = k\nabla^2 T$$

These governing equations are solved numerically to predict the flow and thermal behavior of the cooling fluid inside the microchannel heat sink.

For the initial investigation, steady-state, incompressible, single-phase flow with constant thermophysical properties is assumed. Laminar flow modelling is used where the Reynolds number supports this assumption. Conjugate heat transfer between the solid heat sink and the cooling fluid is included.

EXPERIMENTAL STUDY

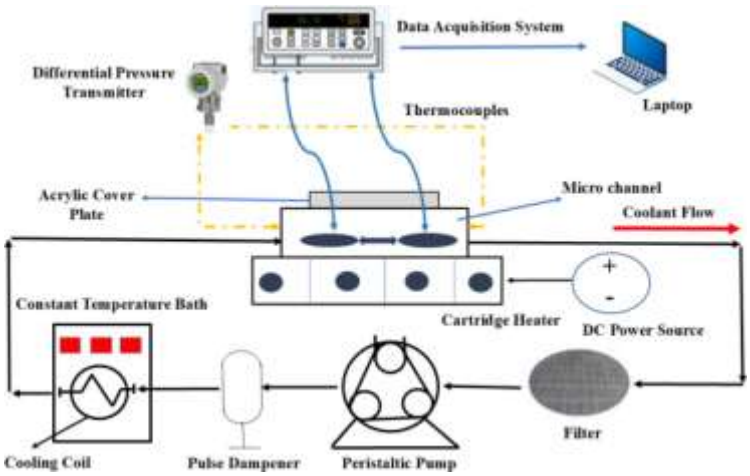
1. Experimental Investigation Overview

The experimental study of heat transfer enhancement in microchannel heat sinks focuses on evaluating the thermal and hydraulic performance of different microchannel configurations under controlled operating conditions. The investigation is designed to examine the influence of channel geometry, coolant flow rate, inlet temperature, and applied heat flux on heat dissipation capability.

The study combines CFD-based numerical simulations with a proposed experimental arrangement to understand fluid flow behavior, temperature distribution, pressure drop, and overall cooling effectiveness. Rectangular, wavy, ribbed, and pin-fin microchannel heat sinks are considered for comparative evaluation.

2. Experimental Setup and Apparatus

An experimental test facility is proposed to investigate the thermal performance of microchannel heat sinks. The setup consists of a microchannel heat sink, coolant circulation system, heating arrangement, temperature measurement sensors, pressure sensors, and data acquisition equipment.



The major experimental components include:

1. Microchannel Heat Sink: Fabricated using copper or aluminium to provide an effective heat transfer surface.
2. Heating Element: An electrical heater is attached to the bottom surface to generate a controlled heat flux.
3. Cooling System: A water circulation pump supplies coolant through the microchannels.
4. Flow Meter: Measures the volumetric flow rate of the cooling fluid.
5. Thermocouples: Measure inlet temperature, outlet temperature, and heat sink surface temperatures.
6. Pressure Sensors: Measure pressure at the inlet and outlet to determine pressure drop.
7. Data Acquisition System: Records experimental measurements for further analysis.

3. Experimental Design and Parameters

The experimental investigation considers different operating conditions to evaluate the influence of flow and thermal parameters.

The following values represent proposed experimental operating ranges.

Experimental Parameter	Proposed Range
Working Fluid	Water
Heat Sink Material	Copper / Aluminium
Inlet Temperature	293–303 K
Inlet Velocity	0.1–2.0 m/s
Applied Heat Flux	50–200 W/cm²
Channel Configuration	Rectangular, Wavy, Ribbed, Pin-Fin
Flow Condition	Laminar
Measurement Type	Thermal and Hydraulic

The same operating conditions are maintained for all configurations wherever possible to ensure a fair comparison.

4. Experimental Procedure

The experimental procedure is divided into several stages to ensure accurate and repeatable measurements.

Step 1: Preparation of Microchannel Heat Sink

Different microchannel geometries are fabricated or prepared using suitable manufacturing techniques. The dimensions and surface conditions of each heat sink are inspected before testing.

Step 2: Installation of Heating Arrangement

An electrical heating element is attached to the bottom surface of the heat sink. Thermal insulation is provided around the test section to minimize heat losses to the surroundings.

Step 3: Coolant Circulation

Water is supplied through the microchannels using a controlled pumping system. The inlet flow rate and coolant temperature are adjusted according to the selected experimental conditions.

Step 4: Temperature Measurement

Thermocouples are installed at suitable locations to measure inlet temperature, outlet temperature, and surface temperature at different positions along the heat sink.

Step 5: Pressure Measurement
Pressure sensors are connected at the inlet and outlet to determine the pressure drop across the microchannel heat sink.

Step 6: Data Collection
Measurements are recorded after the system reaches steady-state operating conditions. Each experimental condition is repeated to improve measurement reliability.

Step 7: Performance Evaluation
The collected data are used to calculate heat transfer rate, Nusselt number, friction factor, thermal resistance, and pumping power.

RESULTS & ANALYSIS

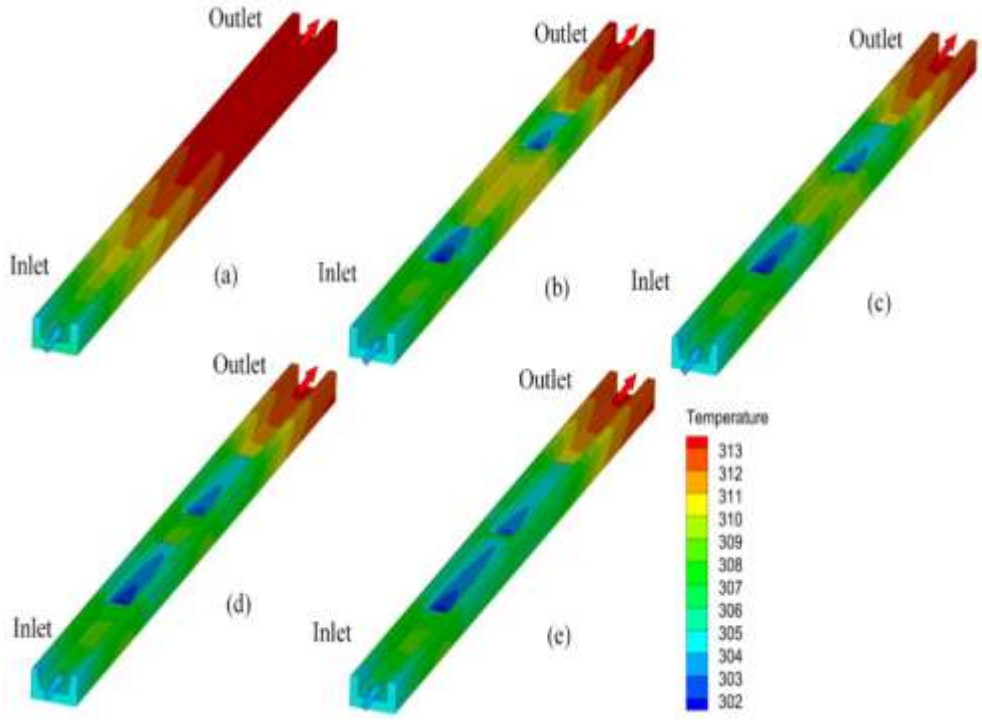
1. Overview of Numerical and Experimental Results

The results and analysis of CFD-based heat transfer enhancement in microchannel heat sinks focus on evaluating the thermal and hydraulic performance of different channel configurations. The investigation considers rectangular, wavy, ribbed, and pin-fin microchannels to understand their influence on heat dissipation, temperature distribution, pressure drop, and pumping power requirements.

The major performance indicators considered in this study include Reynolds number, Nusselt number, heat transfer coefficient, thermal resistance, friction factor, and pressure drop. These parameters provide a comprehensive understanding of the effectiveness of different microchannel designs under varying operating conditions.

2. Temperature Distribution Analysis

Temperature distribution is an important parameter for evaluating the cooling effectiveness of microchannel heat sinks. CFD simulations provide detailed temperature contours that illustrate the thermal behavior of the heat sink and cooling fluid.



The analysis considers the maximum wall temperature, average wall temperature, and temperature uniformity across different microchannel configurations.

The rectangular microchannel serves as the reference configuration. Modified geometries, such as wavy and ribbed channels, are expected to improve fluid mixing and thermal boundary layer disruption. Pin-fin configurations may also enhance heat dissipation by increasing the effective heat transfer area.

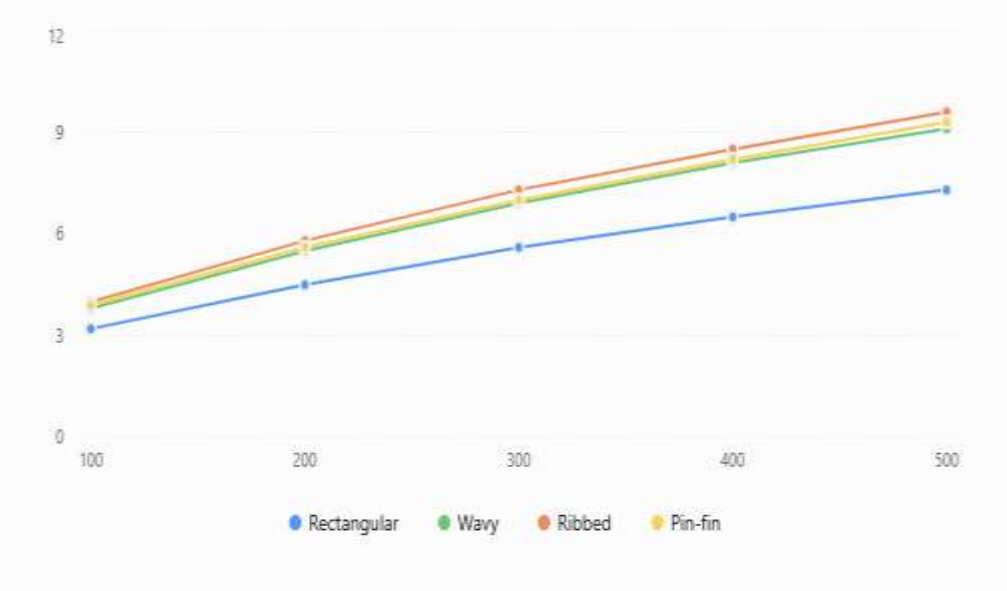
A reduction in maximum wall temperature indicates improved cooling performance and reduced risk of thermal damage to electronic components.

3. Effect of Reynolds Number on Heat Transfer
The Reynolds number determines the flow characteristics inside microchannels and influences convective heat transfer performance.

$$Re = \frac{\rho V D_h}{\mu}$$

As the Reynolds number increases, fluid velocity and convective heat transfer generally increase. However, the corresponding pressure drop may also increase.

Illustrative Reynolds Number vs Nusselt Number
Conceptual trend showing increasing convective heat transfer with Reynolds number; not experimental data.



The illustrative trend suggests that modified channel geometries may produce higher Nusselt numbers than conventional rectangular channels. The actual enhancement depends on channel dimensions, flow regime, and operating conditions.

4. Heat Transfer Coefficient Analysis
The heat transfer coefficient indicates the effectiveness of thermal energy transfer between the heated channel walls and the cooling fluid.

$$h = \frac{Q}{A(T_w - T_b)}$$

The heat transfer coefficient is expected to vary with:

- Coolant inlet velocity.
- Channel hydraulic diameter.
- Fluid thermal conductivity.
- Channel surface geometry.
- Thermal boundary layer development.

Wavy and ribbed microchannels may demonstrate improved convective heat transfer because their geometrical features can promote fluid mixing. Pin-fin structures may also provide increased heat transfer surface area.

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COMPARATIVE ANALYSIS IN TABULAR FORM

The comparative analysis of different microchannel heat sink configurations is essential for evaluating their thermal and hydraulic performance. This study considers four major designs: rectangular, wavy, ribbed, and pin-fin microchannels. The comparison focuses on heat transfer enhancement, pressure drop, thermal resistance, fluid flow characteristics, pumping power, and practical applications.

1. Comparison of Different Microchannel Configurations

Parameters	Rectangular	Wavy	Ribbed	Pin-Fin
Channel Geometry	Straight	Curved	Rib-enhanced	Fin-based
Heat Transfer	Moderate	High	Very High	High
Fluid Mixing	Low	High	Very High	High
Pressure Drop	Low	Moderate	High	Moderate–High
Thermal Resistance	Moderate	Low	Very Low	Low
Manufacturing Complexity	Low	Moderate	Moderate	High
Cooling Effectiveness	Moderate	High	Very High	High
Design Flexibility	High	High	Moderate	High

2. Comparative Analysis of Thermal Performance

Thermal performance is evaluated using the Nusselt number, heat transfer coefficient, maximum wall temperature, and thermal resistance.

Performance Indicators	Rectangular	Wavy	Ribbed	Pin-Fin
Nusselt Number	Reference	Higher	Highest potential	Higher
Heat Transfer Coefficient	Moderate	High	Very High	High
Maximum Wall Temperature	Relatively High	Lower	Potentially Lowest	Lower
Temperature Uniformity	Moderate	Good	Good	Good
Heat Dissipation Capacity	Moderate	High	Very High	High

The comparison indicates that geometrical modifications can improve heat transfer by increasing effective surface interaction and modifying fluid flow patterns. Ribbed configurations may provide substantial enhancement, although their performance depends on rib dimensions, spacing, and flow conditions.

3. Comparative Analysis of Hydraulic Performance

Hydraulic performance is important because improved heat transfer may be accompanied by increased pressure drop and pumping power requirements.

Hydraulic Parameters	Rectangular	Wavy	Ribbed	Pin-Fin
Pressure Drop	Low	Moderate	High	Moderate–High
Friction Factor	Low	Moderate	High	Moderate–High
Pumping Power	Low	Moderate	High	Moderate–High
Flow Resistance	Low	Moderate	High	Moderate–High
Flow Disturbance	Low	Moderate	High	High

Rectangular microchannels generally provide lower hydraulic resistance because of their simple geometry. Wavy, ribbed, and pin-fin configurations may produce greater flow disturbance, resulting in enhanced heat transfer but potentially higher pumping requirements.

4. Comparison of CFD Simulation Parameters

CFD Parameters	Rectangular	Wavy	Ribbed	Pin-Fin
Flow Distribution	Uniform	Periodically disturbed	Strongly disturbed	Complex
Velocity Profile	Relatively Smooth	Variable	Non-uniform	Non-uniform
Thermal Boundary Layer	Relatively Stable	Disrupted	Strongly Disrupted	Modified
Pressure Distribution	Gradual Variation	Periodic Variation	Localized Variations	Complex Variation
Numerical Modelling	Simple	Moderate	Moderate–Complex	Complex

SIGNIFICANCE OF THE TOPIC

The study entitled "CFD Analysis of Heat Transfer Enhancement in Microchannel Heat Sinks" is significant because of the increasing demand for efficient thermal management technologies in modern electronic devices, semiconductor systems, high-performance computing, and advanced engineering applications. As electronic components become smaller and more powerful, the amount of heat generated within compact spaces increases considerably. Effective heat dissipation is therefore essential for maintaining operational stability, improving energy efficiency, and extending equipment lifespan. Microchannel heat sinks provide a promising solution because of their compact dimensions, high surface-area-to-volume ratio, and enhanced heat transfer capabilities.

1. Improvement in Thermal Management Efficiency
Microchannel heat sinks provide effective cooling by increasing the contact area between the cooling fluid and heated surfaces. The investigation of different channel geometries helps identify configurations that can improve heat removal, reduce maximum surface temperature, and minimize thermal resistance.

2. Advancement in Electronic Cooling Technologies
Modern electronic devices, microprocessors, integrated circuits, and semiconductor components generate substantial heat during operation. The proposed research supports the development of advanced cooling systems capable of maintaining suitable operating temperatures and preventing thermal damage.

3. Importance of Computational Fluid Dynamics
CFD analysis provides detailed information about fluid flow, temperature distribution, pressure variation, and heat transfer characteristics within microchannels. It allows researchers to investigate different design configurations without depending entirely on expensive physical experiments.

4. Optimization of Microchannel Geometries
The study evaluates rectangular, wavy, ribbed, and pin-fin microchannel configurations. Their comparative analysis helps identify geometrical modifications that may enhance convective heat transfer, improve fluid mixing, and increase cooling effectiveness.

LIMITATIONS & DRAWBACKS

Although microchannel heat sinks offer significant potential for enhancing heat transfer and improving thermal management, their design, numerical modelling, and practical implementation involve several limitations. The CFD analysis of heat transfer enhancement in microchannel heat sinks provides valuable insights into fluid flow and thermal behavior; however, certain technical, computational, experimental, and economic challenges must be considered.

1. High Pressure Drop
One of the major limitations of microchannel heat sinks is the high pressure drop associated with fluid movement through small channels. Modified geometries, such as ribbed, wavy, and pin-fin configurations, may increase flow resistance and require additional pumping power.

2. Manufacturing Complexity
Microchannel heat sinks require precise manufacturing processes because of their small dimensions and complex geometrical structures. Producing uniform channels, ribs, and pin-fin arrangements can increase fabrication difficulty and manufacturing costs.

3. Limitations of CFD Modelling
CFD simulations depend on mathematical assumptions, numerical methods, boundary conditions, and mesh quality. Inaccurate modelling assumptions may produce deviations between predicted and actual thermal performance.

4. Mesh Dependency and Computational Cost
Accurate CFD analysis requires sufficiently refined computational meshes, particularly near channel walls and complex geometrical features. Fine meshes increase computational time, memory requirements, and processing costs.

5. Coolant Selection Challenges
The performance of microchannel heat sinks depends significantly on the thermophysical properties of the working fluid. Water is commonly used, but its use may introduce corrosion, leakage, and freezing concerns under certain operating conditions. Alternative coolants and nanofluids may also involve higher costs and stability challenges.

6. Flow Maldistribution
In multiple parallel microchannels, coolant may not distribute uniformly among all channels. Uneven flow distribution can create localized hot spots, reduce cooling effectiveness, and produce inconsistent thermal performance.

7. Clogging and Fouling Problems
The small hydraulic diameter of microchannels makes them susceptible to blockage caused by suspended particles, impurities, deposits, and corrosion products. Clogging can restrict coolant flow, increase pressure drop, and reduce heat transfer performance.

CONCLUSION

The study entitled "CFD Analysis of Heat Transfer Enhancement in Microchannel Heat Sinks" highlights the importance of advanced cooling technologies for improving thermal management in modern electronic and engineering applications. Microchannel heat sinks have emerged as promising solutions because of their compact structure, high surface-area-to-volume ratio, and ability to dissipate considerable amounts of heat from small surfaces. The investigation emphasizes the role of Computational Fluid Dynamics (CFD) in understanding fluid flow characteristics, temperature distribution, pressure variations, and heat transfer mechanisms within different microchannel configurations.

The proposed numerical investigation considers four major microchannel geometries: rectangular, wavy, ribbed, and pin-fin configurations. Their thermal and hydraulic performance is evaluated using important parameters such as Reynolds number, Nusselt number, heat transfer coefficient, friction factor, pressure drop, pumping power, and thermal resistance. The comparative analysis suggests that modified channel geometries can provide improved heat transfer through enhanced fluid mixing, increased heat transfer surface area, and disruption of thermal boundary layers. In particular, ribbed and pin-fin configurations offer potential advantages for applications requiring higher heat dissipation, while conventional rectangular channels provide relatively simple manufacturing and lower hydraulic resistance.

The study also highlights the importance of maintaining a balance between heat transfer enhancement and hydraulic performance. Increasing coolant velocity and introducing complex channel geometries may improve convective heat transfer; however, these modifications can also increase pressure drop and pumping power requirements. Therefore, selecting an optimal microchannel configuration requires a comprehensive evaluation of thermal efficiency, hydraulic resistance, manufacturing complexity, and operational cost. Multi-objective optimization techniques, including Response Surface Methodology and Genetic Algorithms, can support the identification of suitable geometrical and operating parameters.

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