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Original Article

Numerical Investigation on Thermohydraulic Performance of Semi Wavy Micro Channel Inserted With Different Fin Shapes Using Water, Ethylene Glycol-Based Nano Fluids

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Abstract

This study presents a numerical investigation into the thermohydraulic performance of a semi-wavy microchannel integrated with various fin geometries, aimed at enhancing heat transfer characteristics. The microchannel model, with dimensions of 10 mm × 10 mm × 8 mm, was designed using SolidWorks and made of Al-Si-10Mg alloy, known for its excellent thermal conductivity and mechanical strength. To enhance object efficiency here different fin shapes, rectangular, and square were embedded within the channel to analyse their influence on thermal performance.

The computational simulations were conducted under three different mass flow rates of 100 ml/min, 250 ml/min, and 475 ml/min. To further augment the heat transfer rate, three types of working fluids were considered: (i) a mixture of 60% water and 40% ethylene glycol, (ii) water with 2% TiO_2 nanoparticles, and (iii) water with 5% TiO_2 nanoparticles. A uniform heat flux of 30 W/m² was applied at the base of the microchannel.

The results obtained include the variation of velocity, pressure, and temperature at both inlet and outlet, along with the calculation of heat transfer coefficient and Nusselt number for each case. The comparative analysis highlights the combined effect of fin geometry, nanofluid concentration, and flow rate on overall thermal performance, indicating the optimal configuration for micro-scale cooling applications.

Introduction

Efficient thermal management is becoming increasingly essential in a wide range of engineering applications such as micro-electronics, power systems, biomedical devices, and aerospace technology. As the performance and compactness of devices continue to improve, they tend to generate more heat in smaller volumes. This leads to elevated heat fluxes that, if not properly managed, can negatively affect the reliability, efficiency, and lifespan of the components. Therefore, researchers and engineers have continuously sought innovative methods to enhance heat transfer while maintaining a compact form factor and manageable pressure drops.

One of the most promising solutions to this challenge is the implementation of microchannel heat sinks (MCHS). Microchannels are miniature flow passages with hydraulic diameters typically below 1 mm. They offer high surface-area-to-volume ratios, which facilitate efficient heat transfer between the fluid and the channel walls. Introduced first by Tuckerman and Pease in the 1980s for cooling high-performance electronic chips, microchannels have since gained wide acceptance in modern thermal systems.

Despite their advantages, conventional straight microchannels often suffer from laminar flow conditions and the development of thermal boundary layers along the channel walls, which limit heat transfer rates. As a result, efforts have been made to improve their performance by modifying the channel geometry. One such modification is the use of wavy or semi wavy microchannel designs, which introduce periodic changes in the flow direction. These wavy geometries generate flow separation and secondary vortices that disrupt the boundary layer and enhance fluid mixing, thus improving convective heat transfer.

Another strategy for improving thermal performance involves inserting fins or extended surfaces within the microchannel. The use of different fin shapes such as circular, square, or rectangular can significantly influence the flow field, pressure distribution, and temperature gradients within the channel. Fins increase the contact surface area between the fluid and the solid domain, and their strategic placement can

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promote turbulence and re-circulation zones that enhance heat removal capabilities. The interaction between channel geometry and fin structure is thus an important consideration in advanced heat sink design.

In parallel with geometric enhancements, the development of nanofluids has opened new avenues for improving heat transfer. Nanofluids are engineered by dispersing nanosized particles (typically less than 100 nm in diameter) into base fluids like water, ethylene glycol, or oils. Due to the high thermal conductivity of the nanoparticles and the increased surface area for heat exchange, nanofluids have shown superior heat transfer characteristics compared to conventional fluids. Commonly used nanoparticles include metals (like copper), metal oxides (such as TiO_2, Al_2O_3), and carbon-based materials (like graphene and carbon nanotubes).

The combination of modified microchannel geometries, fin insertions, and advanced heat transfer fluids presents a highly efficient and compact cooling strategy suitable for next-generation thermal systems. Among the geometric modifications, semi wavy channels with different fin shapes offer a unique opportunity to study the interactions between fluid dynamics and thermal behaviour in complex flow domains. When such structures are combined with nanofluids, particularly those based on mixtures of water and ethylene glycol with nanoparticles like TiO_2, the potential for thermohydraulic enhancement becomes even greater.

Given the increasing demands for efficient and compact thermal management solutions, it is essential to explore and understand the complex interplay between channel design, fin geometry, and fluid properties. This investigation contributes to that effort by examining how these factors can be optimized to achieve better thermohydraulic performance, balancing high heat transfer rates with acceptable flow resistance. This research area holds significant promise for practical applications in electronics cooling, automotive thermal systems, and micro-scale energy devices.

Nano fluid

A Nano fluid is a fluid containing nanometer-sized particles, called nanoparticles. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid the nanoparticles used in Nano fluids are typically made of metals, oxides, carbides, or carbon nanotubes. Common base fluids include water, ethylene glycol and oil.

Nanofluids have novel properties that make them potentially useful in many applications in heat transfer, including microelectronics, fuel cells, pharmaceutical processes, and hybrid-powered engines, engine cooling/vehicle thermal management, domestic refrigerator, chiller, heat exchanger, in grinding, machining and in boiler flue gas temperature reduction. They exhibit enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid. Knowledge of the rheological behavior of Nano fluids is found to be critical in deciding their suitability for convective heat transfer applications. Nanofluids also have special acoustical properties and in ultrasonic fields display additional shear-wave reconversion of an incident compressional wave; the effect becomes more pronounced as concentration increases.

In analysis such as computational fluid dynamics (CFD), Nano fluids can be assumed to be single phase fluids; however, almost all new academic papers use a two-phase assumption. Classical theory of single phase fluids can be applied, where physical properties of Nano fluid is taken as a function of properties of both constituents and their concentrations.[10] An alternative approach simulates Nano fluids using a two-component model.

The spreading of a Nano fluid droplet is enhanced by the solid-like ordering structure of nanoparticles assembled near the contact line by diffusion, which gives rise to a structural disjoining pressure in the vicinity of the contact line. However, such enhancement is not observed for small droplets with diameter of nanometer scale, because the wetting time scale is much smaller than the diffusion time scale.

Synthesis

Nanofluids are produced by several techniques:

1. Direct Evaporation (1 step)
2. Gas condensation/dispersion (2 step)
3. Chemical vapor condensation (1 step)
4. Chemical precipitation (1 step)
5. Bio-based (1 step)

Several liquids including water, ethylene glycol, and oils have been used as base fluids. Although stabilization can be a challenge, on-going research indicates that it is possible. Nano-materials used so far in Nano fluid synthesis include metallic particles, oxide particles, carbon nanotubes, grapheme Nano-flakes and ceramic particles.

A bio-based, environmentally friendly approach for the covalent functionalization of multi-walled carbon nanotubes (MWCNTs) using clove buds was developed. There are no any toxic and hazardous acids which are typically used in common carbon nanomaterial functionalization procedures, employed in this synthesis. The MWCNTs are functionalized in one pot (one step) using a free radical grafting reaction. The clove-functionalized MWCNTs are then dispersed in distilled water (DI water), producing a highly stable MWCNT aqueous suspension (MWCNTs Nano fluid).

Smart cooling Nano fluids

Realizing the modest thermal conductivity enhancement in conventional Nano fluids, a team of researchers at Indira Gandhi Centre for Atomic Research Centre, Kalpak am developed a new class of magnetically polarizable Nano fluids where the thermal conductivity enhancement up to 300% of base fluids is demonstrated. Fatty-acid-capped magnetite nanoparticles of different sizes (3-10 nm) have been synthesized for this purpose. It has been shown that both the thermal and rheological properties of such magnetic Nano fluids are tunable by varying the magnetic field strength and orientation with respect to the direction of heat flow. Such response stimuli fluids are reversibly switchable and have applications in miniature devices such as micro- and Nano-electromechanical systems. In 2013, Azizian et al. considered the effect of an external magnetic field on the convective heat transfer coefficient of water-based magnetite Nano fluid experimentally under laminar flow regime. Up to 300% enhancement obtained at Re=745 and magnetic field gradient of 32.5 mT/mm. The effect of the magnetic field on the pressure drop was not as significant.

Ethylene Glycol

In recent decades, the continuous miniaturization of electronic components and the growing demand for compact, high-performance devices have intensified the need for efficient heat dissipation techniques. Traditional cooling fluids like water and air have reached their performance limitations, prompting researchers to explore alternative coolants that can deliver higher thermal conductivity and better temperature control. Among these alternatives, ethylene glycol (EG) has emerged as a widely used base fluid, particularly in applications that require extended stability, corrosion resistance, and freeze protection.

Ethylene glycol is an organic compound commonly used in automotive and industrial cooling systems due to its favorable thermophysical properties. It offers a relatively high boiling point and low freezing point, making it ideal for systems exposed to varying environmental conditions. When mixed with water in specific proportions (commonly 60:40 or 50:50), ethylene glycol enhances the fluid's thermal stability while maintaining moderate viscosity. This blend provides a reliable balance between heat transfer capacity and operational safety in microchannel-based cooling systems.

In microchannels, where fluid flow and heat exchange occur on a very small scale, the properties of the working fluid significantly affect performance parameters such as pressure drop, velocity distribution, and temperature gradients. The higher viscosity of EG compared to pure water can increase flow resistance, but its higher boiling point and anti-corrosive behavior help maintain consistent thermal performance over time. Furthermore, ethylene glycol serves as a suitable carrier fluid for nanoparticles when formulating nanofluids, due to its compatibility with a wide range of nanomaterials.

In the context of thermal enhancement, EG-based nanofluids provide a promising platform for combining chemical stability with improved heat transfer characteristics. The use of water-ethylene glycol mixtures as base fluids, particularly when enhanced with nanoparticles like TiO_2, opens up new possibilities for efficient and compact cooling in microchannel applications.

TiO_2 Nanofluids in Microchannel Heat Transfer

The emergence of nanofluids—fluids engineered by suspending nanoparticles in base fluids—has revolutionized the field of heat transfer in recent years. Among the various nanoparticles investigated, titanium dioxide (TiO_2) has gained considerable attention due to its excellent thermal stability, non-toxicity, corrosion resistance, and affordability. When dispersed in traditional heat transfer fluids such as water or water-ethylene glycol mixtures, TiO_2 nanoparticles significantly enhance the thermal conductivity of the base fluid, thereby improving its overall heat transfer performance.

TiO_2 nanofluids work on the principle that nanoscale particles can interact with thermal fields more effectively due to their large surface area-to-volume ratio. These particles improve energy transport within the fluid, reducing thermal resistance and increasing convective heat transfer. In microchannel systems, where flow is typically laminar and surface interactions dominate, such enhancements can play a crucial role in achieving higher thermal efficiency without increasing the size or power requirements of the system.

One of the key advantages of TiO_2 is its chemical inertness, which ensures long-term stability of the nanofluid without significant agglomeration or sedimentation. It is also less likely to react with other materials in the system, making it suitable for a wide range of industrial and electronic cooling applications. The thermal conductivity enhancement of TiO_2 nanofluids is further influenced by the volume concentration of nanoparticles. For instance, concentrations of 2% and 5% by volume have been shown to produce noticeable improvements in heat transfer performance, although they may also lead to increased pressure drops due to higher viscosity.

In the context of semi wavy microchannels with internal fins, the integration of TiO_2 nanofluids offers a dual benefit: enhanced thermal conductivity from the nanoparticles and improved convective flow from geometric modifications. This synergistic combination holds significant promise for developing compact, energy-efficient cooling systems suitable for modern high-heat-flux environments.

Literature Survey

High-Performance Heat Sinking for VLSI – IEEE Electron Device Letters [1] Tuckerman and Pease (1981) Tuckerman and Pease were pioneers in the development of microchannel heat sinks. Their work focused on improving thermal management in very-large-scale integration (VLSI) circuits by embedding microchannels into substrates to dissipate heat efficiently. The microchannels significantly increased the surface area for convective heat transfer, enabling efficient cooling at the micro-scale. Their experiments showed a considerable enhancement in heat removal compared to traditional heat sinks, which laid the groundwork for modern microchannel cooling technologies. This study is particularly relevant to the current work, as it establishes the effectiveness of using microchannels for high heat flux applications. The concept introduced in this paper influences the present research, which uses a semi-wavy microchannel structure to further increase the heat transfer rate. Although their research did not explore fin shapes or nanofluids, it serves as a foundational reference for microchannel-based thermal management systems, validating the relevance of microchannels in compact and high-performance cooling devices.

[2] Kandlikar (2005) High Flux Heat Removal with Microchannels – A Roadmap of Challenges and Opportunities Heat Transfer Engineering S.G. Kandlikar provided a comprehensive review of microchannel heat sink performance and the various factors influencing heat transfer, such as flow patterns, channel shapes, surface enhancements, and coolant selection. His work highlighted the growing demand for compact cooling systems in electronics, automotive, and biomedical industries. Kandlikar argued that enhanced surface geometries like grooves, fins, and wavy structures could disrupt boundary layers and induce secondary flows, significantly improving convective heat transfer. He also discussed the trade-offs between heat transfer and pressure drop, emphasizing the need for optimized designs. This directly supports the current study's goal of investigating different fin shapes in a semi-wavy channel to maximize thermal performance while maintaining manageable pressure drops. Although nanofluids were not a central focus, Kandlikar acknowledged their potential to further boost performance. His work provides a strong theoretical foundation for combining geometric and fluidic enhancements in microchannel systems, aligning well with the objectives of this numerical investigation.

[3] Xuan and Li (2000) Heat Transfer Enhancement of Nanofluids – International Journal of Heat and Fluid Flow. Xuan and Li introduced the concept of nanofluids suspensions of nanoparticles in base fluids like water or ethylene glycol—to improve heat transfer rates in various thermal systems. Their research showed that even low concentrations of nanoparticles like TiO_2, Al_2O_3, and CuO could significantly enhance the thermal conductivity of the base fluid, leading to better cooling performance. The study also discussed the role of particle size, shape, and volume fraction in determining overall heat transfer characteristics. One of their major findings was that nanofluids improve thermal conductivity without a drastic increase in viscosity, making them ideal for compact cooling applications such as microchannels. This directly supports the present study, where TiO_2-based nanofluids are used at different

concentrations (2% and 5%) to evaluate their effect on thermal behavior. The authors' insights validate the use of nanofluids in your simulation and provide a scientific rationale for selecting TiO_2 nanoparticles in water and ethylene glycol mixtures to enhance thermohydraulic performance.

Objective

To design a semi-wavy microchannel structure with integrated fins of different shapes using SolidWorks. To investigate the heat transfer performance of the microchannel using different nanofluids and flow rates. To analyse and compare the thermohydraulic parameters such as:

- Temperature distribution
- Pressure drop
- Velocity variation
- Heat transfer coefficient
- Nusselt number

To determine the most effective fin shape and fluid combination for enhancing thermal performance under a constant heat flux.

Methodology

Geometry Design

- Model the semi-wavy microchannel (10 mm × 10 mm × 8 mm) in SolidWorks.
- Insert three different fin geometries: rectangular, and square, between the channel walls.

Material Selection

- Use Al-Si-10Mg as the microchannel material due to its high thermal conductivity.

Fluid Preparation:

- Simulate the flow of three types of coolants:
  - 60% Water + 40% Ethylene Glycol
  - 98% Water + 2% TiO_2 Nanoparticles
  - 95% Water + 5% TiO_2 Nanoparticles

Boundary Conditions:

- Apply three mass flow rates: 100 ml/min, 250 ml/min, and 475 ml/min.
- Impose a constant heat flux of 30 W/m² at the base of the microchannel.

Numerical Simulation:

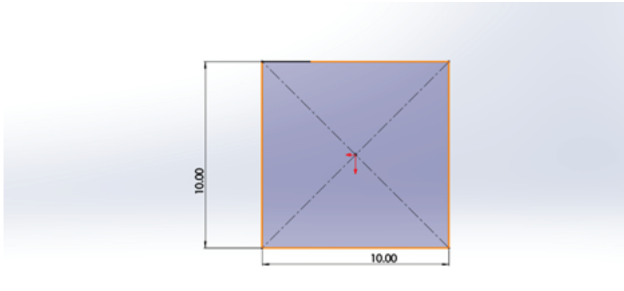
- Import the geometry into ANSYS Fluent or similar CFD software.
- Define fluid properties, mesh the geometry, and apply boundary conditions.
- Solve the steady-state flow and thermal equations.

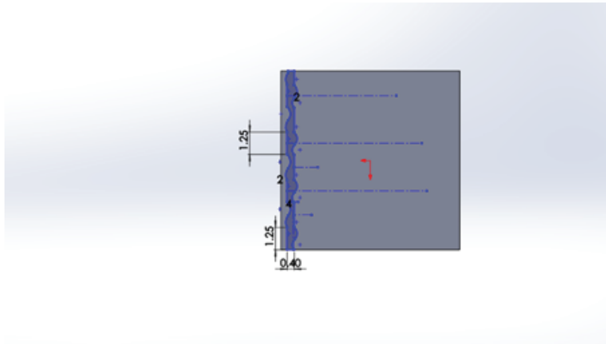
Post-Processing and Analysis:

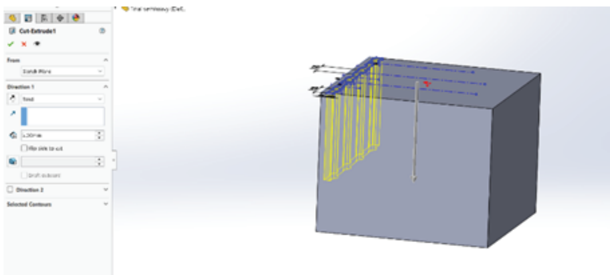
- Record temperature, pressure, and velocity values at inlet and outlet.
- Calculate heat transfer coefficient and Nusselt number for each configuration.

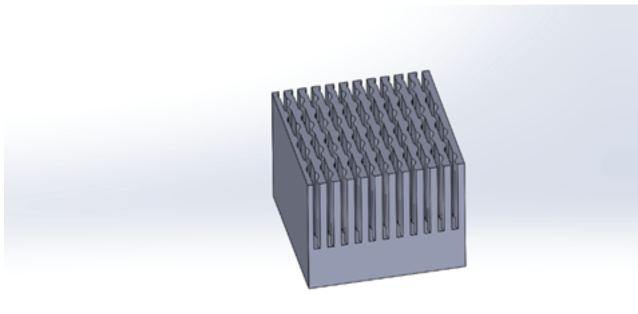
Compare and interpret results to identify the best performing setup

Design process step by step

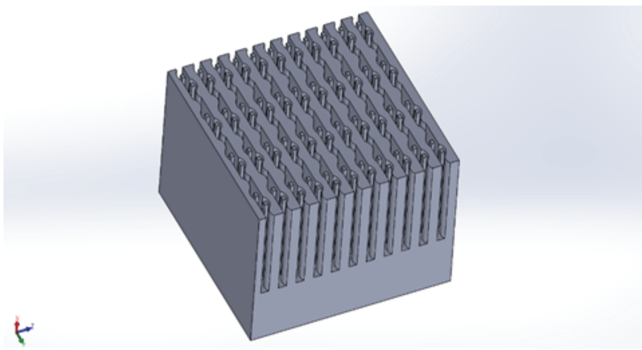




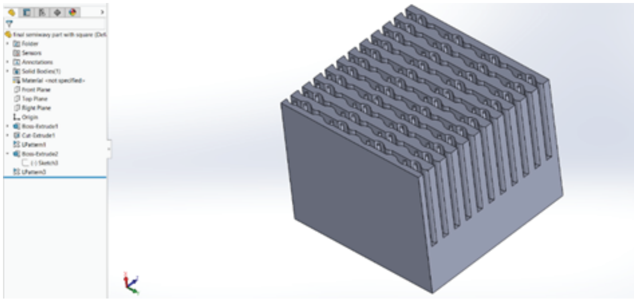




Semi wavy micro channel



Semi wavy micro channel with rectangular fins



Semi wavy micro channel with square fins

Material selection for this semi wavy micro channel

In this al-si-10mg material chosen to do analysis on this object,

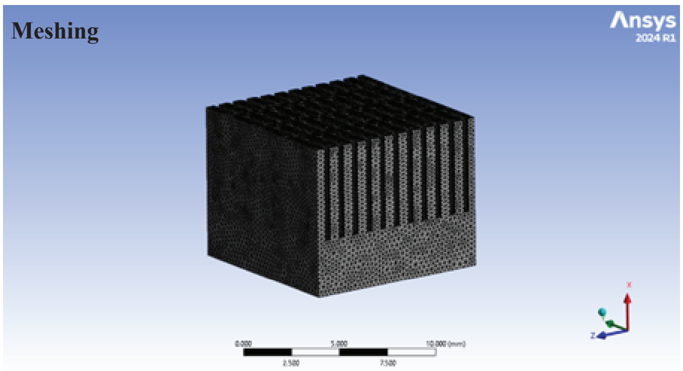
Al-Si-10Mg is a cast aluminum alloy containing approximately:

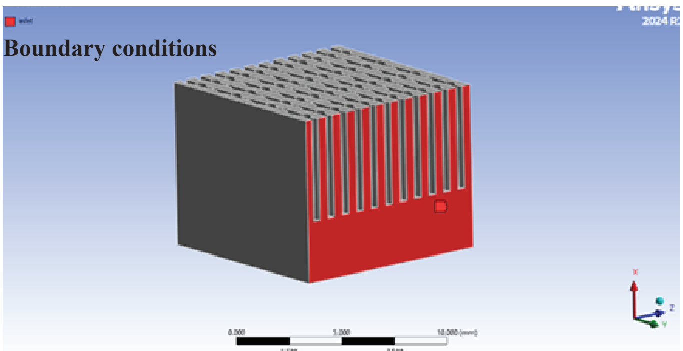
- 10% Silicon (Si)
- 0.3–0.6% Magnesium (Mg)
- The balance being Aluminum (Al)

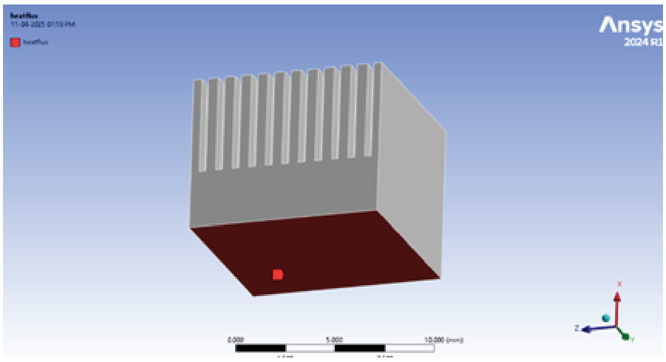
It is widely used in additive manufacturing (like Selective Laser Melting - SLM) and casting applications due to its lightweight, good mechanical strength, and excellent thermal properties.

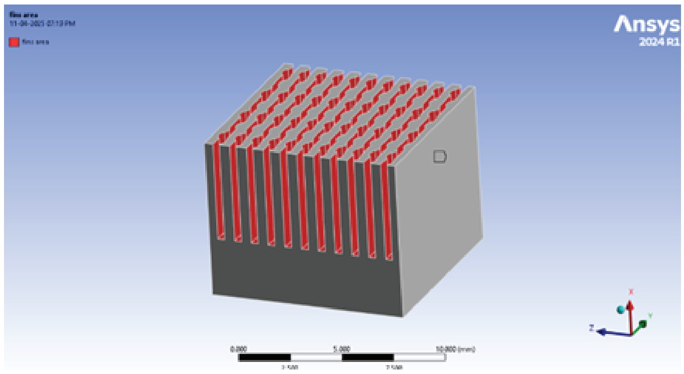
Density	2.65 – 2.68 g/cm³
Thermal Conductivity	~150–180 W/m·K
Specific Heat Capacity	~0.9 J/g·K
Melting Point	~570–595°C
Tensile Strength (SLM)	~320–400 MPa
Young's Modulus	~70 GPa

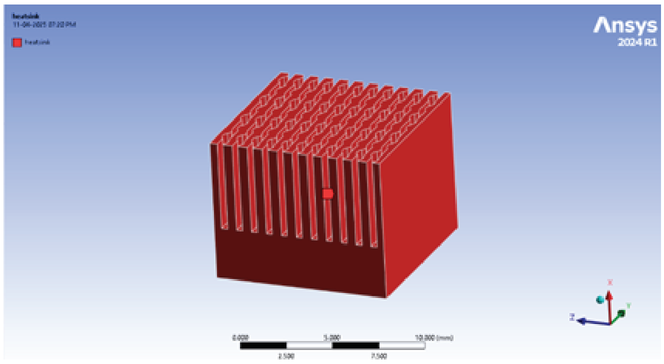
Analysis process











Boundary Conditions

- Inlet:
  - Mass Flow Inlet
  - Four mass flow rate cases applied:
    - 100ml/min
    - 250 ml/min
    - 475 ml/min
  - Temperature at inlet: 298 K
- **Outlet:**
  - Pressure Outlet
  - Gauge pressure: 0 Pa (atmospheric)
  - Backflow temperature: 300 K
- **Bottom Surface of Heat Sink:**
  - Wall heat flux condition
  - Applied heat flux: 30 W/m²
- **Walls (microchannel walls and outer surfaces):**
  - No-slip condition
  - Adiabatic for unheated walls
  - Symmetry applied if only one channel was simulated

for computational efficiency

Solution Methods

- Pressure–Velocity Coupling: SIMPLE
- Spatial Discretization:
  - Gradient: Least Squares Cell-Based
  - Pressure: Standard
  - Momentum & Energy: Second-Order Upwind

Initialization

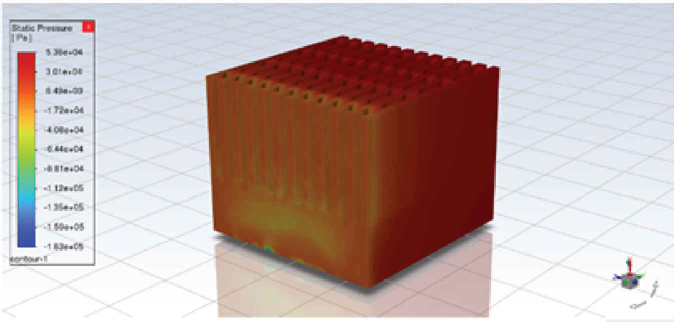
- Initialization Type: Hybrid
- Run until convergence (residuals < 1e-6 for energy and < 1e-3 for continuity and momentum)

Mass flow rate 100 ml/min

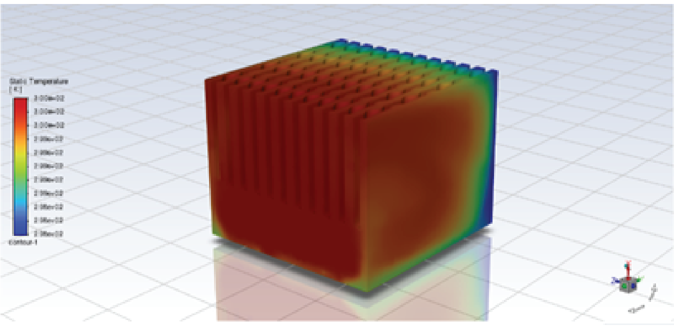
Semi wavy

Water 60% with 40 % ethaline glycol

Pressure.



Temperature



Inlet outlet temperature

```
Area-Weighted Average
   Static Temperature                       [K]
----------------------- --------------------
                  inlet                  298
                 outlet            299.92748
```

Velocity inlet outlet

```
Area-Weighted Average
   Velocity Magnitude                     [m/s]
----------------------- --------------------
                  inlet          0.027606044
                 outlet            3.8276178
```

Fin area temperature

```
Area-Weighted Average
   Static Temperature                       [K]
----------------------- --------------------
               insulate            299.80479
```

Nusselt number

```
  Area-Weighted Average
 Surface Nusselt Number
------------------------ --------------------
                heatflux            6.0470234
```

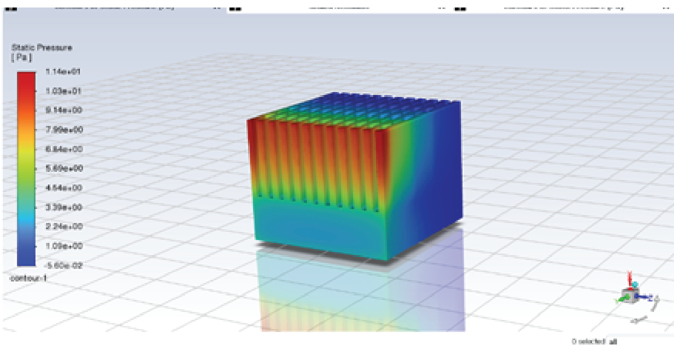
Heat transfer coefficient

```
            Mass-Weighted Average
Wall Adjacent Heat Transfer Coef.            [W/(m^2 K)]
--------------------------------- --------------------
                         heatsink            1754.8923
                 ---------------- --------------------
```

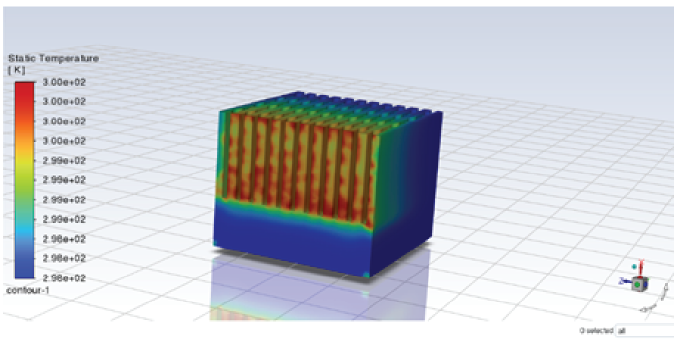
Semi wavy

Water 98% with 2 % Tio2

Pressure



Temperature



Inlet outlet temperature

Area-Weighted Average Static Temperature	[K]
inlet	298
outlet	298.86042

Velocity inlet outlet

Area-Weighted Average Velocity Magnitude	[m/s]
inlet	0.02711215
outlet	0.026569135

Fin area temperature

Area-Weighted Average Static Temperature	[K]
insulate	298.77705

Nusselt number

Area-Weighted Average Surface Nusselt Number	
heatflux	4.8353479

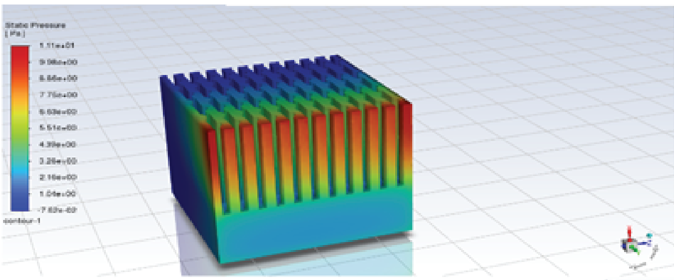
Heat transfer coefficient

Mass-Weighted Average Wall Adjacent Heat Transfer Coef.	[W/(m^2 K)]
heatsink	2139.6427

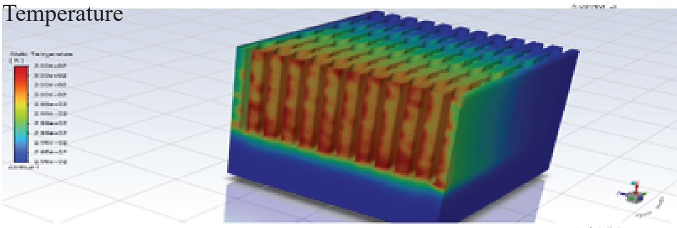
Semi wavy

Water 95% with 5 % Tio2

Pressure



Temperature



Inlet outlet temperature

Area-Weighted Average Static Temperature	[K]
inlet	298
outlet	298.90802

Velocity inlet outlet

Area-Weighted Average Velocity Magnitude	[m/s]
inlet	0.024843057
outlet	0.024306084

Fin area temperature

Area-Weighted Average Static Temperature	[K]
fins_area	298.84234

Nusselt number

Area-Weighted Average Surface Nusselt Number	
heatflux	4.7599309

Heat transfer coefficient

Mass-Weighted Average Wall Adjacent Heat Transfer Coef.	[W/(m^2 K)]
heatsink	2173.7468

Conclusion

The present numerical investigation provides a comprehensive assessment of the thermohydraulic performance of a semi-wavy microchannel embedded with different fin shapes and operating under various flow conditions using advanced working fluids. The study successfully demonstrated how geometric modifications, such as incorporating rectangular and square fins, significantly influence the heat transfer characteristics within the microchannel environment. The finned configurations helped disturb the thermal boundary layer, leading to enhanced convective heat transfer.

The analysis, performed using a SolidWorks-designed Al-Si-10Mg microchannel model, showed that both fluid properties and fin geometry play a critical role in determining the overall system performance. Among the working fluids analysed, nanofluids based on TiO_2 (especially at 5% concentration) offered a notable improvement in heat transfer coefficients and Nusselt numbers compared to the base mixture of 60% water and 40% ethylene glycol. However, this enhancement came with a corresponding increase in pressure drop, underlining the need for a trade-off between thermal performance and pumping power.

Additionally, an increase in mass flow rate from 100 ml/min to 475 ml/min further boosted heat removal capacity due to higher convective effects, although diminishing returns were observed at higher flow rates in terms of efficiency. The combined impact of fin geometry, flow rate, and nanofluid concentration indicated that rectangular fins coupled with a 5% TiO_2 nanofluid and a mid-level flow rate provided an optimized balance between heat transfer and pressure losses.

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