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Investigating Heat Transfer and Flow Characteristics under Different Wall Heating Conditions in Novel Micro Pin-Fin Heat Sinks

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Abstract – The escalating power density in electronic devices demands effective and sustainable heat dissipation solutions. Micro pin-fin designs offer potential enhancements to thermal management in electronic cooling. Consequently, this short paper numerically investigates heat transfer and flow characteristics in micro pin-fin heating under distinct wall heating conditions. The results indicate that the new scutoid design exhibits a commendable heat transfer coefficient of 3298 W/m²K, with the lowest pressure drop and operating base temperatures. Thus, the findings provide a foundation for future designs and efficient heat transfer strategies.

***Keywords*:** heat sinks; heat transfer; thermal management; CFD; micro pin-fins; microchannels

1. Introduction

The surge in miniaturised electronic devices in the Industry 4.0 era is reshaping various sectors. Modern components including computer chips, high-power LEDs, power amplifiers, and lasers, designed with microscale components, generate substantial heat during continuous use. This heat adversely impacts system performance and risks damaging critical components. Efficient thermal management is now a paramount design requirement for handling high heat fluxes in miniature systems. In a global push for sustainability, ineffective thermal management leads to energy wastage, contributing to unsustainable impacts. Therefore, addressing the thermal challenges of electronic devices is crucial for optimal performance, prolonged component lifespan, and alignment with global sustainability goals.

Currently, tackling cooling challenges in electronic devices is a pivotal engineering obstacle. With the availability of advanced manufacturing techniques for microfabrication and metal-based 3D printing, heat sinks based on micro pin-fin configurations have emerged as promising solutions for effective electronics cooling and generated considerable interest across various applications [1]. However, there is still a lack of consensus on optimal microscale heat transfer strategies and the underlying physics required to meet future heat transfer requirements [2]. Consequently, further studies are essential to provide novel insights into new designs that integrate micro pin-fin and heat transfer.

Thus, this short paper aims to numerically examine heat transfer and flow under different wall heating conditions in a novel micro pin-fin heat sink. Building on extant literature findings, the investigation analyses how changes in wall heating conditions impact heat transfer and flow performance. The objective of this research is to bridge gaps in microscale heat transfer, offering insights for efficient cooling systems. The paper is structured around the research aim, with the initial sections covering model design, methods, simulation, results, and evaluation. Subsequent sections include discussions, conclusions, and recommendations for further research.

2. Numerical Methods and Materials

In this research, two designs were compared. The first base design featured inline rectangular pin fins (RF) and was used for numerical validation from the works of [3]; The second design, containing pentagonal-hexa-prism fins (SF), drew inspiration from a skin cell shape called scutoid. The SF combined the effects of two different shapes and offered new insights. Then, a CFD study analysed heat transfer and flow characteristics to understand the underlying physics. The microfin geometries, heat sink design, along with the different wall heating setup, are depicted in Fig. 1; the heat sinks had identical dimensions and number of pin fins (17 × 34).

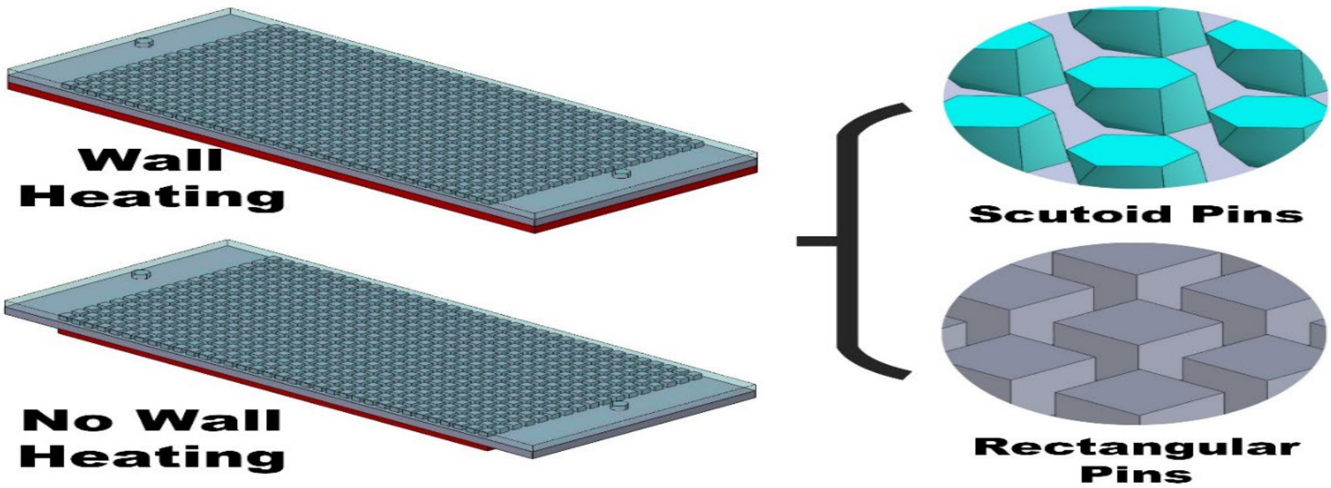

Fig. 1: Micro pin-fin heat sink designs

2.1. Governing Equations

There are some disagreements between authors regarding the flow characteristics and Reynolds Number (Re) at which turbulent flow occurs at the microscale. However, 550≥Re≥400 generally fall in the laminar region. The governing equations and assumptions used for modelling were adapted/modified from previous works [5] and are as follows:

$$Continuity\ equation: \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

$$Energy\ equation\ (fluid): \rho_f \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) = \mu \cdot \mathrm{Pr}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + S_t(fluid) \quad (2)$$

$$Heat\ transfer\ coefficient\ (HTC): h = \frac{\dot{m}_a c_p (T_o - T_i)}{A_s[T_b - \left(\frac{T_i + T_o}{2}\right)]} \quad (3)$$

Where, u, v, w - velocity components; x, y, z - directions; ρ_f – fluid density; μ - dynamic viscosity; Pr - Prandtl number; S_t - energy equation source term; T, T_b, T_i, T_o are fluid, base, inlet, and outlet temperatures, respectively; m - mass flow rate; A_s - base area where heat is applied; C_p – specific heat.

2.2. Model Pre-processing and Numerical Validation

ANSYS Fluent Mesh software helped to create three mesh sizes for fluid (water) and solid (aluminium) domains. Some of the goals whilst using CFD is to improve mesh/accuracy but reduce the time and cost of simulation. Therefore, the mesh grid independence test was done using a velocity metric ($\boldsymbol{V_{max}}$) at outlet; the numerical validation was done using the base temperature ($\boldsymbol{T_b}$) from [3]. Table 1 provides the mesh statistics and related data for the pre-processing.

Table 1: Numerical Validation and Grid independence test results.

Mesh (No. of Nodes)	$\boldsymbol{V_{max}}$ **(**$\boldsymbol{Re = 550}$**)**	$\boldsymbol{T_b}$ **(CFD)**	**%Error,** $\boldsymbol{T_b}$ **[3]**	$\boldsymbol{V_{max}}$ **(**$\boldsymbol{Re = 400}$**)**	$\boldsymbol{T_b}$ **(CFD)**	**%Error,** $\boldsymbol{T_b}$ **[3]**
Mesh I (58443)	0.246 m/s	329.3 K	2%	0.179 m/s	337.6 K	18%
Mesh II (76000)	0.240 m/s	325.6 K	13%	0.178 m/s	337.5 K	18%
Mesh III (143695)	0.245 m/s	328.5 K	4%	0.174 m/s	334.0 K	7%

The minimal difference between the $\boldsymbol{V_{max}}$ values and acceptable %error for $\boldsymbol{T_b}$ highlights the success in numerical validation. Mesh (III) was preferred for simulations, with orthogonal quality above 0.70 (considered good). The refinement ratio of Mesh (II)/(I) and (III)/(II) were both above 1.3, further supporting the grid independence and numerical results [4].

3. Results and Discussion

Fig. 2 presents CFD simulation results for temperature variations and velocity streamlines. Boundary conditions included an initial inlet temperature of 298 K, zero outlet pressure, and Re = 550, with a system heat flux of 37.2 kW/m^2. NWH designs (RF, SF) lacked extended heat flux, while SFX and RFX designs had heated inlet and outlet regions. WH designs exhibited higher temperature saturation near the outlet, contrasting with NWH designs showing cold spots near the inlet. Due to the geometric influences and potential laminar boundary layers, the RF design displayed thick boundary layers, but generally, there were no significant difference between NWH and WH. Overall, WH designs had more evenly distributed distinct temperature regions and higher base temperatures than NWH designs. Also, SF and SFX designs showed potential flow recirculation and turbulence near the right side of the inlet, influencing boundary layer formations.

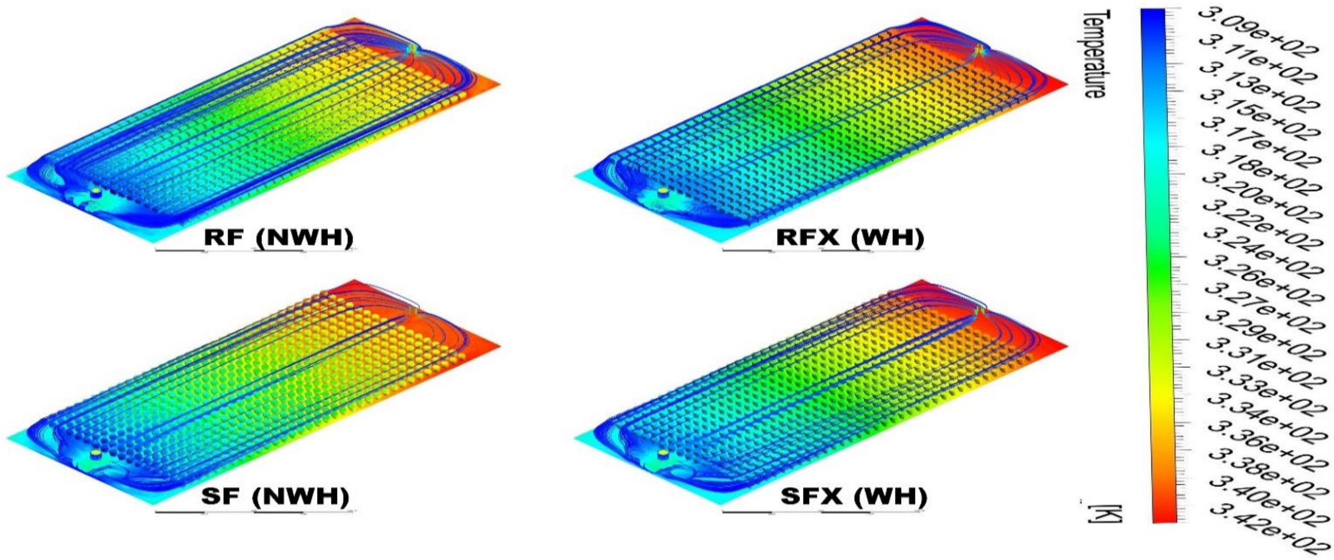

Fig. 2: Temperature distribution from the top view and outlets

It can be said that the three most important considerations for heat sink designs include pressure drop, HTC, and the base operating temperature. Fig. 3 shows the 3D surface plot used for visualising the data and comparing the designs.

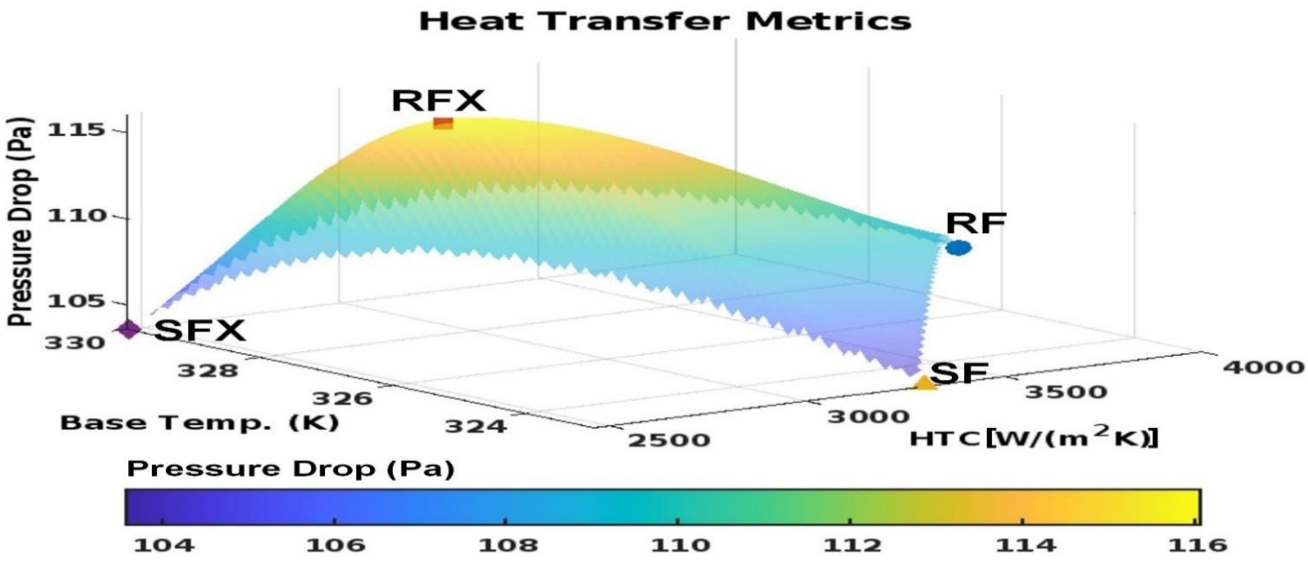

Fig. 3: Pressure distribution in the heat sinks

In analysing the performance metrics of the four designs—RF, RFX, SF, and SFX—several observations are made. While RF boasts the highest Heat Transfer Coefficient (HTC) at 3892 W/m^2K, the slightly elevated operated Base

Temperature (BT) of 326 K and pressure drop values may impact its overall performance. On the other hand, SF demonstrated a commendable HTC of 3298 W/m^2K and, notably, the lowest operating base temperature at 323 K, suggesting superior continuous heat dissipation capabilities. Additionally, when considering the importance of Pressure Drop (PD) for efficient fluid flow and pumping power, SFX emerges with the lowest value at 103.6 Pa, closely followed by SF at 103.65 Pa. Despite RF's impressive HTC, the combination of SF's substantial HTC, lowest base temperature, and lowest pressure drop makes SF as the overall best option, striking a balance between efficient heat transfer and fluid dynamics. Also, it should be noted that the WH designs showed lower HTC values and higher BT for both type of pins.

The study explored the influence of wall heating conditions, particularly the impact of extended heat flux and new micro pin-fin geometries on heat distribution and fluid dynamics. The extended heat flux resulted in distinct and uniformly distributed heat regions. However, in wall-heated (WH) designs, the absence of pin-fins in the heated inlet and outlet areas affected heat dissipation, leading to a higher overall operating base temperature than non-wall-heated (NWH) designs. Notably, the data indicated that pressure drop values were predominantly influenced by pin-fin geometry rather than wall heating conditions, as evidenced by the lower pressure drop values in designs like SF and SFX. Despite SF operating at a lower base temperature with approximately 4% less pressure drop than RF, its HTC was roughly 15% less than RF. Therefore, this discrepancy was due to the reduced surface area/volume of the SF pins in the new scutoid designs. Additionally, the complex geometry may have induced turbulence, potentially disrupting the flow and thermal resistance, which could have been better computed using different turbulence models; some research has indicated turbulent transition regions in microscale flows for Re>400 under various operating conditions [6]. Nonetheless, the study's significance lies in giving insights into design optimisations, understanding trade-offs between operating parameters, and for researching future assessments of complex pin-fins under different operating conditions for advancing sustainable cooling technology.

4. Conclusion

This short study conducted a comparative analysis of a novel micro pin-fin geometry using numerical simulations to appraise geometric influence, wall heating conditions, and flow and heat transfer characteristics. Key findings concluded that (a) the new scutoid-inspired design (SF) exhibited superior overall heat transfer performance, (b) wall heating adversely affected heat dissipation, despite achieving better heat distribution, and (c) the system's pressure drop was more reliant on geometry than on wall heating conditions.

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