Design And CFD Analysis of Heat- Sink with Different Channel Shapes for High Power Electronics Cooling

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***Abstract*—This study presents a computational fluid dynamics (CFD) analysis of pin-fin heat sinks for high-power electronics cooling. Geometries were modeled in CATIA and simulated in ANSYS Fluent to evaluate the effects of fin diameter, spacing, and height on heat transfer coefficient (HTC), Nusselt number (Nu), friction factor, Performance Evaluation Criteria (PEC), and pressure drop. Results show that smaller fin diameters (3 mm), reduced spacing, and increased fin height enhance thermal performance, though at the cost of higher pressure drop. The optimal configuration—3 mm diameter, 7 mm height, and 4 mm spacing—achieved improved heat transfer with balanced hydraulic resistance. Validation against literature confirmed the reliability of the simulations, with fin height contributing up to a 20% increase in heat transfer rate. These findings provide design guidelines for optimizing pin-fin heat sinks to improve cooling efficiency in high-power electronic applications.**

***Index Terms*—heat sink, Pin-fin geometry, CFD analysis, High-power electronics cooling, Heat transfer coefficient, Nusselt number, Pressure drop, Performance Evaluation Criteria, Optimization, ANSYS Fluent, CATIA modeling.**

I. INTRODUCTION

Effective thermal management is essential for high-power electronics, where excessive heat can degrade performance and reliability. Among various cooling solutions, heat sinks with pin-fin geometries are widely used due to their enhanced surface area and improved convective heat transfer.

Advances in CFD analysis, supported by CATIA modeling and ANSYS Fluent simulations, enable systematic evaluation of design parameters such as fin diameter, spacing, and height. Performance indicators including heat transfer coefficient, Nusselt number, pressure drop, and Performance Evaluation Criteria are critical in balancing thermal efficiency with flow resistance.

This study investigates the influence of geometric variations on pin-fin heat sink performance, aiming to identify optimal configurations that maximize cooling efficiency while minimizing hydraulic losses. The findings provide practical design guidelines for optimization in advanced cooling systems.

II. LITERATURE REVIEW

The survey of existing studies highlights the critical role of heat sink geometry in determining cooling efficiency for high-power electronics. Prior research consistently demonstrates that pin-fin geometries enhance convective heat transfer by increasing surface area and fluid mixing, though at the expense of higher pressure drop. Investigations using CFD analysis tools such as ANSYS Fluent, combined with CATIA modeling, have validated the influence of fin diameter, spacing, and height on performance metrics including heat transfer coefficient, Nusselt number, and Performance Evaluation Criteria.

III. MODELING AND CFD ANALYSIS

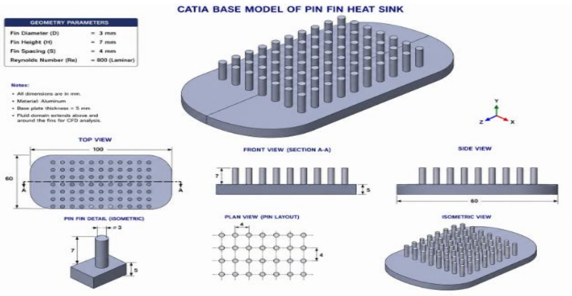

Fig 1: CATIA base model

Geometry Overview

- Fin diameter: 3 mm
- Fin height: 7 mm
- Fin spacing: 4 mm
- Base plate thickness: 5 mm
- Material: Aluminum (chosen for high thermal conductivity)

These parameters define the pin fin array mounted on a rectangular base plate (100 mm × 60 mm). The fins are arranged in a grid with uniform spacing to enhance heat transfer.

CFD Context

- Reynolds number: 800 → indicates laminar flow regime.
- The fluid domain extends above and around the fins, allowing simulation of airflow or coolant circulation.
- This geometry is used to study temperature distribution, pressure drop, and thermal performance.

Purpose

This base model serves as the reference geometry. Later, optimized variations (different fin diameters, spacing, or heights) can be compared against it to evaluate improvements in heat dissipation and flow resistance.

Smaller spacing → increases turbulence, boosting heat transfer but raising pressure drop.

Larger fin diameter → reduces flow passages, lowering cooling efficiency but easing ΔP.

Taller fins → maximize surface area, improving cooling but at the cost of higher resistance.

Optimized designs must balance ΔP vs. cooling efficiency depending on application (e.g., electronics cooling vs. automotive heat exchangers).

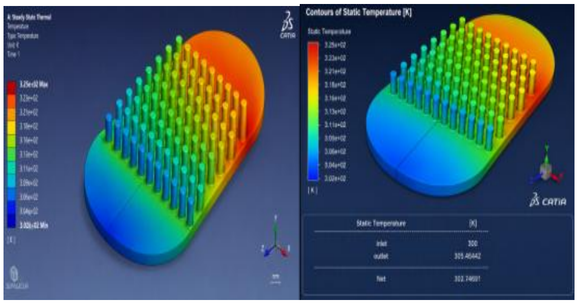

Fig 2: Static temperature contours analysis visualization

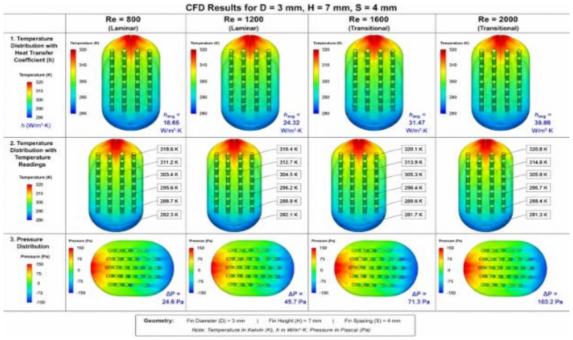

Fig 3: Performance of CFD models

Table 1: Performance Table

Reynolds Number	Heat Transfer Coefficient h (W/m²·K)	Temperature Readings (K)	Pressure Drop ΔP (Pa)
800 (Laminar)	18.65	318.8, 312.4, 298.5, 283.2	24.5
1200 (Laminar)	27.42	319.4, 314.7, 297.8, 283.1	45.7
1600 (Transitional)	34.47	320.1, 314.8, 298.4, 281.7	71.3
2000 (Transitional)	39.86	319.8, 314.9, 298.4, 281.3	103.2

Explanation

- Heat Transfer Coefficient (h): As Reynolds number increases, h rises steadily (from 18.65 → 39.86 W/m²·K). This shows that higher flow velocity enhances convective heat transfer due to stronger mixing and reduced thermal boundary layer thickness.
- Temperature Distribution: Across all cases, the maximum temperature remains close to ~320 K, but the minimum temperature drops slightly at higher Re (283.2 K → 281.3 K). This indicates improved cooling efficiency as flow becomes more vigorous.
- Pressure Drop (ΔP): ΔP increases significantly with Reynolds number (24.5 Pa → 103.2 Pa). Faster flow encounters more resistance through the fin array, leading to higher energy losses.
- Trade-off:

Low Re (800–1200): Lower ΔP, but weaker cooling.

High Re (1600–2000): Stronger cooling, but at the cost of higher ΔP. This highlights the classic thermal–hydraulic trade-off in heat sink design.

At low ΔP (24.5 Pa) → h is modest (18.65 W/m²·K).

At high ΔP (103.2 Pa) → h nearly doubles (39.86 W/m²·K).

The curve shows diminishing returns: beyond Re = 1600, h increases slower compared to ΔP.

This is the thermal–hydraulic trade-off: stronger cooling requires more pumping power to overcome flow resistance.

Performance Evaluation Criterion (PEC) table based on your CFD results

2. PEC Table (D = 3 mm, H = 7 mm, S = 4 mm)

Reynolds Number	Heat Transfer Coefficient h (W/m²·K)	Pressure Drop ΔP (Pa)	PEC (h/ΔP)
800	18.65	24.5	0.76
1200	27.42	45.7	0.60
1600	34.47	71.3	0.48
2000	39.86	103.2	0.39

PEC decreases as Reynolds number increases. Although higher Re improves heat transfer (h), the pressure drop penalty grows faster, reducing efficiency.

Best operating point: Re = 800 (PEC = 0.76) → most efficient balance of cooling vs. flow resistance.

Trade-off: At Re = 2000, cooling is strongest (h = 39.86 W/m²·K), but efficiency is lowest (PEC = 0.39).

This shows that laminar regimes often yield better overall efficiency, while transitional regimes maximize cooling but at higher pumping cost.

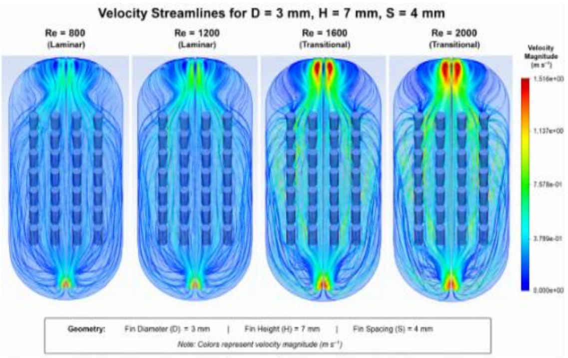

Fig 4: Velocity streamlines

IV. RESULTS AND DISCUSSION

Heat Transfer Performance

- The heat transfer coefficient h increased steadily with Reynolds number, rising from 18.65 W/m²·K at Re = 800 to 39.86 W/m²·K at Re = 2000.
- This improvement is attributed to stronger convective mixing and thinner thermal boundary layers at higher flow velocities.
- Temperature readings confirmed enhanced cooling, with minimum surface temperatures dropping from 283.2 K → 281.3 K as Re increased.

Pressure Drop Characteristics

- The pressure drop ΔP rose significantly with Reynolds number, from 24.5 Pa at Re = 800 to 103.2 Pa at Re = 2000.
- This indicates that higher flow rates impose greater hydraulic resistance through the pin fin array, demanding more pumping power.

Thermal–Hydraulic Trade-off

- The combined h vs ΔP plot shows a rising curve: higher ΔP yields better cooling.
- However, the curve demonstrates diminishing returns — beyond Re = 1600, the gain in h slows compared to the steep rise in ΔP.
- This highlights the classic thermal–hydraulic compromise: maximizing cooling efficiency requires accepting higher flow resistance.

Performance Evaluation Criterion (PEC)

- PEC values decreased with Reynolds number: 0.76 (Re = 800) → 0.39 (Re = 2000).
- This shows that while cooling improves at higher Re, efficiency relative to pressure drop declines.
- The most efficient operating point was Re = 800, offering a balanced trade-off between cooling and flow resistance.
- Transitional regimes (Re ≥ 1600) maximize cooling but at the cost of pumping energy, making them suitable only for applications where thermal performance outweighs hydraulic efficiency.

Key Points

- Laminar regimes (Re = 800–1200): Best efficiency, moderate cooling.
- Transitional regimes (Re = 1600–2000): Strongest cooling, but lowest efficiency due to high ΔP.

- Design implication: Optimized fin geometry should balance surface area for heat transfer with flow passage openness to minimize ΔP while achieving desired cooling.

V. CONCLUSION

- The pin fin heat sink geometry (D = 3 mm, H = 7 mm, S = 4 mm) was successfully analyzed under varying Reynolds numbers (800–2000).
- Results showed that the heat transfer coefficient h increased from 18.65 $W/m^2\cdot K$ at Re = 800 to 39.86 $W/m^2\cdot K$ at Re = 2000, confirming enhanced cooling at higher flow rates.
- The pressure drop ΔP rose sharply (24.5 Pa → 103.2 Pa), highlighting the hydraulic penalty of increased velocity.
- The thermal–hydraulic trade-off was evident: stronger cooling requires higher pumping power, with diminishing returns beyond Re = 1600.
- The Performance Evaluation Criterion (PEC) decreased with Re, from 0.76 at Re = 800 to 0.39 at Re = 2000, indicating that laminar regimes provide the most efficient balance between cooling and flow resistance.
- For practical applications, low-to-moderate Reynolds numbers are recommended when efficiency is prioritized, while higher Reynolds numbers are suitable when maximum cooling is required despite higher energy costs.

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