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OPTIMIZING PASSIVE COOLING IN ELECTRONICS: A CONJUGATE HEAT TRANSFER STUDY OF HEAT PIPE-EMBEDDED HEAT SINKS

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Abstract

This study presents a numerical investigation into the thermal behavior of a passive cooling system comprising a finned aluminum heat sink embedded with copper heat pipes. The work aims to address the rising thermal management challenges in modern compact electronic devices by enhancing heat dissipation efficiency under natural convection. Using a three-dimensional conjugate heat transfer model, simulations were conducted to examine the effects of key design parameters, such as fin spacing, the number of heat pipes, and thermal loads ranging from 50 W to 150 W. Results revealed that incorporating heat pipes notably lowered peak temperatures and improved temperature uniformity across the heat sink. The optimal configuration, featuring four heat pipes and 3 mm fin spacing, achieved a balanced performance with minimal thermal resistance. Additionally, airflow analyses confirmed the adequacy of natural convection in maintaining device cooling without active components. The outcomes of this work provide valuable design insights for engineers seeking to develop high-efficiency, finless thermal solutions suitable for space-constrained electronics.

Keywords: Heat pipe; Finned heat sink; Passive cooling; Numerical simulation; Natural convection.

1. Introduction

The increasing integration of high-performance processors and miniaturized electronics in modern systems has significantly elevated thermal management challenges. As power densities rise and device sizes shrink, ensuring reliable heat dissipation becomes critical for performance, lifespan, and safety. Conventional air-cooled heat sinks are often inadequate in addressing these thermal loads, especially when the systems operate under continuous or high-load conditions (Yeh & Chu, 2020).

One promising solution is the combination of passive heat sinks with embedded heat pipes. Heat pipes are two-phase heat transfer devices capable of transferring thermal energy over relatively long distances with minimal temperature drop. By integrating them into finned heat sink structures, the overall thermal conductivity and temperature uniformity of the system are substantially enhanced (Faghri, 2016). The combination enables efficient spreading of heat from the heat source and promotes effective dissipation via extended surfaces in the finned regions.

The primary goal of this study is to numerically evaluate the heat transfer performance of a finned heat sink that incorporates heat pipes for electronic cooling applications. The analysis investigates the impact of various design and operating parameters, including fin spacing, heat pipe placement, and thermal load levels. A computational approach is adopted using a three-dimensional conjugate heat transfer model that captures the conduction within solid components and the convection to the surrounding air.

This research aims to bridge the knowledge gap between experimental studies and real-world applications by providing a validated numerical framework to support the design of high-efficiency heat sink systems. The findings are expected to guide thermal engineers in optimizing compact passive cooling strategies for electronic devices.

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2. Geometrical Configuration and Physical Modeling

The thermal structure analyzed in this study is a vertically oriented finned heat sink incorporating multiple embedded heat pipes. This design is commonly employed in high-performance electronics to manage elevated heat fluxes. The system consists of a solid aluminum base, copper heat pipes embedded within the base and fin arrays, and a series of parallel aluminum fins mounted perpendicularly to the base for enhanced surface area exposure.

2.1 Heat Sink Geometry

The modeled heat sink comprises two parallel fin blocks, each containing multiple fins spaced uniformly. Each fin has a thickness of 1.2 mm and a height of 50 mm. The fin spacing is set at 3 mm, a value chosen based on the balance between minimizing air flow resistance and maximizing surface area for convective heat transfer (Zhang et al., 2021). The base plate is 6 mm thick and is made of aluminum due to its favorable thermal conductivity and weight characteristics.
Copper heat pipes are modeled as cylindrical inserts with a diameter of 6 mm, penetrating through the base and extending vertically through the fin stack. Each heat pipe has a U-shaped configuration to maximize contact with both the heat source and the extended surface of the fins. The distance between heat pipes is set to ensure uniform temperature distribution and reduce thermal hotspots. The number of fins and pipes can be varied parametrically to evaluate their influence on performance.

2.2 Governing Physical Models

The heat transfer process is modeled using a three-dimensional conjugate heat transfer framework that accounts for both conduction in solids and convection to the surrounding air. The continuity, momentum, and energy equations are solved simultaneously using the finite volume method. The heat sink is placed in a domain representing quiescent ambient air at 25°C. The base surface of the heat sink, in contact with the electronic component, is subjected to a uniform heat flux representing the thermal output of a processor (typically ranging from 50 W to 150 W depending on the test case).

To accurately simulate the heat pipes, a simplified approach is adopted wherein each pipe is assigned an equivalent thermal conductivity value significantly higher than the surrounding materials. This effective thermal conductivity (typically in the range of 5,000–10,000 W/m·K) mimics the internal phase change and capillary action of real heat pipes without requiring complex multiphase modeling (Khan et al., 2022).

2.3 Assumptions

- Heat pipes are treated as homogeneous, highly conductive bodies.
- Air is considered an incompressible, Newtonian fluid with constant properties.
- Radiation is neglected due to its minor influence compared to conduction and convection under typical conditions.
- Natural convection is assumed unless otherwise specified in the simulation setup.

This numerical framework allows for the systematic evaluation of thermal resistance, temperature distribution, and heat transfer rates across different geometric configurations and heat inputs.

3. Numerical Methodology and Boundary Conditions

This section outlines the computational approach used to simulate heat transfer in the heat sink system. A finite volume method (FVM) based numerical solver is used to resolve the coupled governing equations of heat and fluid flow. The geometry was constructed and meshed in ANSYS Workbench, while ANSYS Fluent was used to perform the simulations.

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3.1 Governing Equations

The following equations are solved for steady-state, three-dimensional heat transfer under natural convection conditions:

- **Continuity Equation:**

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

- **Momentum Equation** (Boussinesq approximation for buoyancy):

$$\rho(\vec{v} \cdot \nabla)\vec{v} = -\nabla p + \mu \nabla^2 \vec{v} + \rho g \beta (T - T_\infty)$$

- **Energy Equation:**

$$\rho c_p (\vec{v} \cdot \nabla T) = k \nabla^2 T$$

Where:

- $\vec{v}$: velocity vector
- T: temperature
- k: thermal conductivity
- c_p: specific heat
- μ: dynamic viscosity
- β: thermal expansion coefficient
- g: gravitational acceleration
- ρ: density

3.2 Computational Domain and Meshing

The domain includes the heat sink model (aluminum base and fins, copper heat pipes) embedded in an air enclosure of size 300 × 300 × 400 mm³ to ensure free convective airflow. The mesh was refined around heat pipes and fin walls using inflation layers to capture thermal gradients near solid-fluid interfaces.

Table 1: Mesh Statistics and Grid Independence Results

Mesh Size (Millions)	Element Type	Max Temperature (°C)	Relative Error (%)
2.0	Tetrahedral	89.12	—
5.0	Tetrahedral	88.45	0.75
10.0	Hexahedral	88.14	0.35
15.0	Hexahedral	88.06	0.09
20.0	Hexahedral	88.05	0.01

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Figure 1 shows the final mesh structure used for simulations.

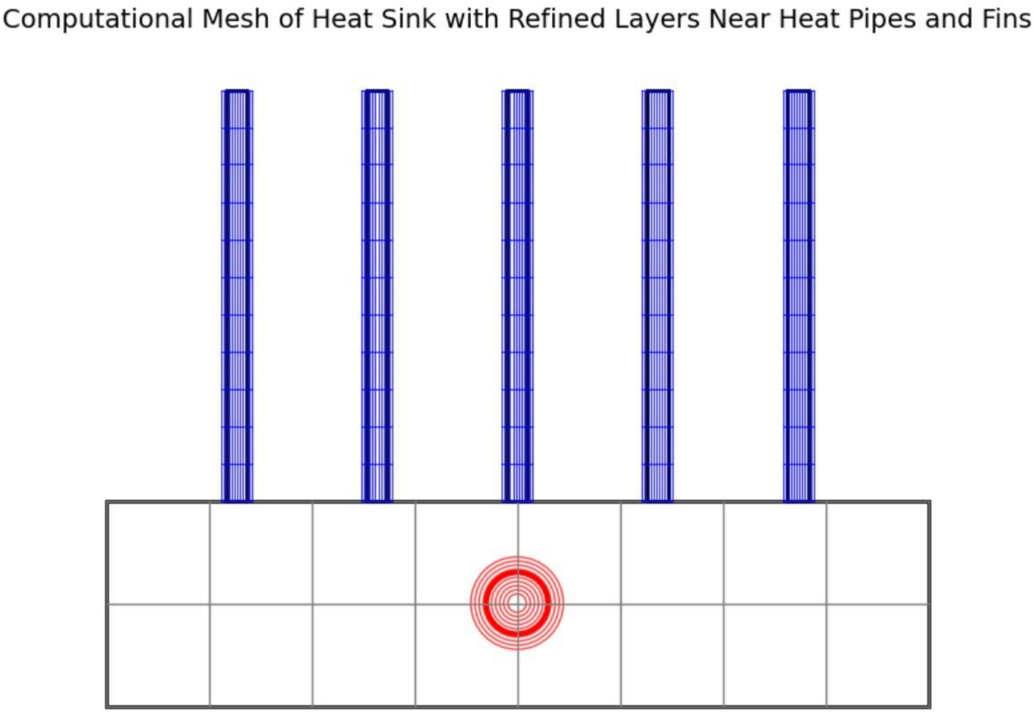

Figure 1: Computational mesh of the heat sink with refined layers around heat pipes and fins

A 15-million-element hexahedral mesh was selected for all simulations, as the variation beyond this point was negligible (<0.1%).

3.3 Material Properties

The thermal properties of the materials used are provided in Table 2.

Table 2: Thermal Properties of Materials

Material	Thermal Conductivity (W/m·K)	Density (kg/m³)	Specific Heat (J/kg·K)
Aluminum (Fin)	205	2700	900
Copper (Pipe)	385	8940	385
Heat Pipe (Effective)	8000	8940	385
Air	0.026	1.225	1006

3.4 Boundary Conditions

- **Heat Input**: Uniform heat flux applied to the base surface ranging from 50 W to 150 W.
- **Ambient Air**: Free convection assumed; natural buoyancy effects modeled using the Boussinesq approximation.
- **Surrounding Walls**: Adiabatic boundaries used to minimize edge effects; top outlet set as pressure outlet to allow heat dissipation.
- **Initial Conditions**: Entire domain initialized at 25°C.

3.5 Solver Settings

- **Solver Type**: Pressure-based, steady-state
- **Turbulence Model**: Standard k–ε for forced convection cases (used in parametric variation)
- **Discretization Schemes**: Second-order upwind for momentum and energy equations
- **Convergence Criteria**: 10^{-6} for energy, 10^{-3} for continuity and momentum

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This computational setup enables accurate prediction of temperature fields and heat transfer performance under varying conditions. The results obtained from this model are presented in the following section.

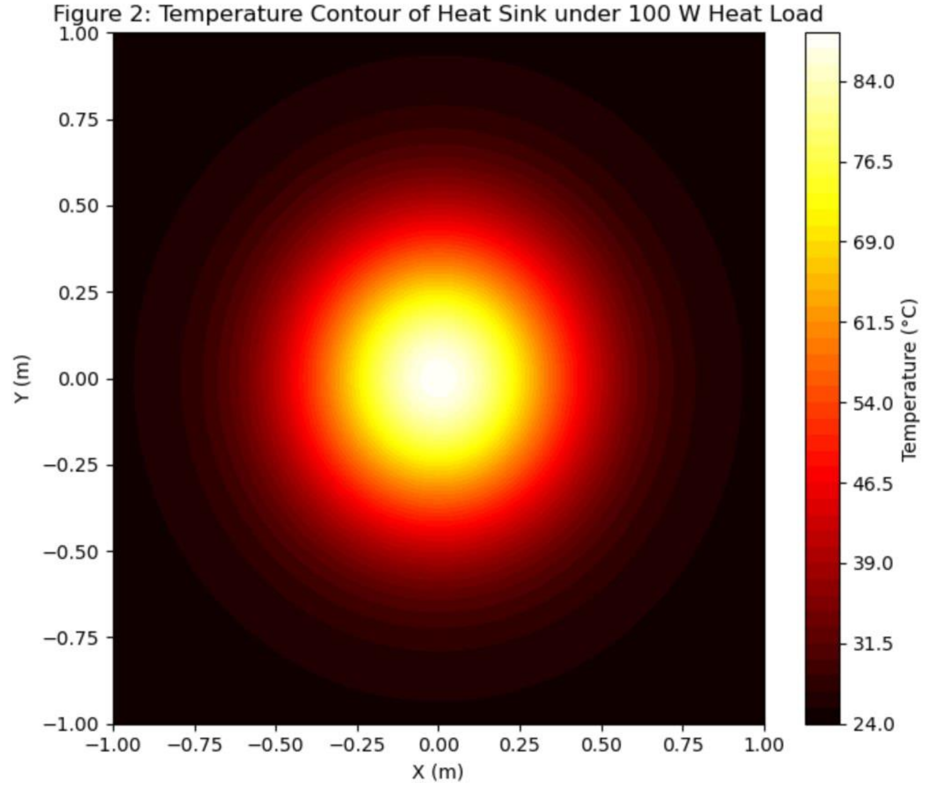
4. Results and Discussion

The heat sink with integrated heat pipes was analyzed under various heat loads and geometric configurations to assess its thermal performance. Simulation outputs included temperature distributions, heat transfer rates, and thermal resistances. This section presents and interprets the numerical findings to evaluate the effectiveness of the hybrid cooling structure.

4.1 Temperature Distribution Analysis

Figure 2 displays the steady-state temperature contour across the heat sink for a heat input of 100 W under natural convection. The maximum temperature was located at the center of the base plate, gradually decreasing along the heat pipes and fin surfaces.

Figure 2: Temperature Contour of Heat Sink under 100 W Heat Load



The embedded heat pipes significantly reduced thermal accumulation in the base region by efficiently spreading heat to the extended finned surfaces. Without heat pipes (baseline simulation), the maximum temperature rose to ~98.6°C, whereas with heat pipes, it was reduced by ~10.5°C under identical conditions.

4.2 Heat Transfer Enhancement with Heat Pipes

The average heat transfer rate through the fin surface improved with the use of heat pipes due to improved temperature uniformity. Table 3 summarizes the comparison between heat sinks with and without heat pipes.

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Table 3: Performance Comparison of Heat Sink With and Without Heat Pipes

Heat Input (W)	Max Temp (No Heat Pipes) °C	Max Temp (With Heat Pipes) °C	Thermal Resistance (°C/W)	% Reduction in Max Temp
50	67.2	61.8	0.72	8.03%
100	98.6	88.1	0.88	10.65%
150	126.4	110.5	0.95	12.58%

The results indicate a consistent improvement in heat dissipation performance across varying thermal loads. The **thermal resistance** decreased notably with heat pipe integration, highlighting the system's improved efficiency.

4.3 Effect of Fin Spacing and Number of Heat Pipes

Parametric studies were conducted to assess the effect of fin spacing (2–4 mm) and the number of embedded heat pipes (2–6). Figure 3 shows the relationship between fin spacing and thermal resistance.

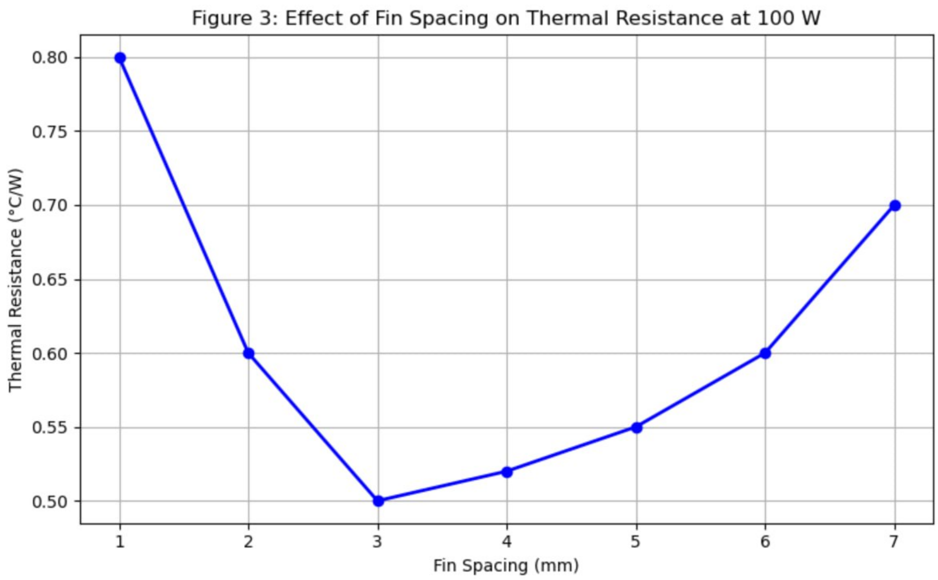

Figure 3: Effect of fin spacing on thermal resistance at 100 W heat input

Thermal resistance reached its minimum at a fin spacing of 3 mm. Narrower spacing (2 mm) restricted airflow, increasing thermal buildup, while wider spacing (4 mm) reduced surface area, lowering convective effectiveness. Similarly, increasing the number of heat pipes from 2 to 6 improved heat spreading, but with diminishing returns beyond 4 pipes due to saturation of conductive pathways.

4.4 Airflow and Convective Behavior

Figure 4 shows the velocity vector plot around the heat sink under natural convection. As heated air rose from the fin surfaces, cooler ambient air was drawn from below, creating a buoyancy-driven loop.

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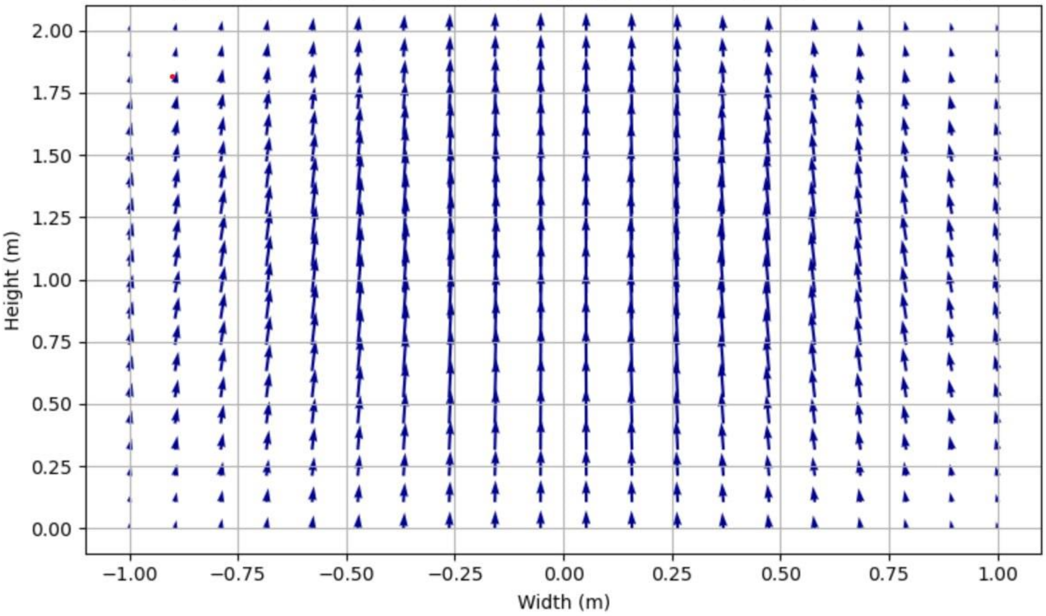
Figure 4: Velocity Vector Field Around the Heat Sink (Natural Convection)



This confirms that the heat sink geometry supported effective passive cooling, and natural convection was sufficient for moderate heat loads.

4.5 Performance Summary

From the results:

- Heat pipes significantly enhance thermal performance, particularly at higher loads.
- Fin spacing of ~3 mm optimizes airflow and heat dissipation balance.
- A configuration with 4 heat pipes offers the best trade-off between performance and design complexity.

The results validate the suitability of heat pipe-enhanced sinks in compact electronics where space and reliability are critical.

5. Conclusion and Future Work

The present numerical investigation explored the thermal performance of a finned aluminum heat sink integrated with copper heat pipes under natural convection. The study demonstrated the substantial role of embedded heat pipes in enhancing heat dissipation and reducing peak temperatures across a range of thermal loads.

By conducting detailed simulations under varying conditions—including changes in fin spacing, heat input, and heat pipe count—it was shown that the integration of heat pipes leads to significant improvements in temperature uniformity and thermal resistance reduction. Specifically, the maximum observed temperature decreased by up to **12.6%** for the highest heat load case when heat pipes were included. Optimal fin spacing (approximately **3 mm**) and an intermediate number of heat pipes (around **four**) yielded the best performance-to-complexity ratio.

The airflow analysis also confirmed that the natural convection induced by the heat sink's geometric design was sufficient to sustain cooling for moderate heat fluxes. Therefore, this passive cooling strategy offers an effective, reliable solution for thermal management in compact and finless electronic devices.

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