Investigating Perforated Heat Sink Using Recycled Cast Blocks for Enhanced Thermal Performance

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Abstract
Effective thermal management has become increasingly important in modern electronic applications due to the increase in power densities and the reduction in the size of components, which requires more exotic heat dissipating technologies to guarantee system reliability and lifespan. Heat sinks remain the leading form of passive cooling, where the complexity of the fin design must be increased to maximize the effectiveness of convective heat transfer. This research investigates whether a perforated heat sink made from recycled aluminum waste can provide improvements in the thermal management of electronics. In particular, it examines whether heat sinks made with circular perforated holes in an overall block of recycled metal will have comparable thermal performance to conventional heat sinks machined from raw metal stock. The results of the experiments are verified and supplemented with detailed ANSYS simulations showing the heat transfer, fluid flow, and temperature distributions of both perforated and slab heat sink geometries under realistic boundary conditions and material properties. The results show that the recycled perforated heat sinks have thermal efficiencies similar to the solid heat sinks, although the temperature gradients and heat dissipation patterns varied slightly. Utilizing recycled aluminum reduces material costs and environmental impacts, and demonstrates the value of sustainable manufacturing processes applied to thermal management systems.

Keywords: *Heat Sinks, Circular perforation fins, Heat transfer enhancement, Performance analysis*

1. Introduction

Effective thermal management has become increasingly important in modern electronic applications due to the increase in power densities and the reduction in the size of components, which requires more exotic heat-dissipating technologies to guarantee system reliability and lifespan[1]. Heat sinks remain the leading form of passive cooling, where the complexity of the fin design must be increased to maximize the effectiveness of convective heat transfer[5]. Among all designs, these have gained considerable interest since their perforations interrupt the thermal boundary layer and enhance airflow through the fin structure, resulting in increased natural convection heat transfer rates and minimized thermal resistance [2].

The perforation geometry — circular, square, triangular, or wavy — and their disposition on the fins (inline, staggered, lateral, or interrupted) significantly affect the performance of the heat sink. For example, Abdel-Shafi and Jassem [3-9] showed experimentally that circular and wavy perforated fins improved air turbulence, thus enhancing thermal dissipation, when compared to solid fins. Likewise, Sahin and Demir [4] discovered that perforated pin fins provided enhanced thermal performance with the added benefits of weight reduction and reduced material requirement. The occurrence of staggered or multi-row perforations can additionally enhance cooling efficiency by facilitating more distributed airflow and higher surface convective heat transfer [10-15].

Natural convection analyses verify that the incorporation of fine perforations enhances heat transfer coefficients and lowers base plate temperature compared with traditional solid fin designs [6-13]. Wadhah Hussein Al-Doori [13] demonstrated that circular perforations increase natural convection heat dissipation compared to rectangular fins. Experimental results by Umesh and Pise [18] support the fact that perforation configurations and inclinations can be optimized in order to improve thermal performance, illustrating the importance of fin orientation and the position of fin holes in convective effectiveness. Moreover, Zan Wu [12] constructed models illustrating the beneficial effect of perforations on natural convection heat transfer from perforated plates, corroborating experimental findings.

Material choice plays a crucial role in augmenting geometric improvements in heat sink design. Recycling cast aluminum blocks as the heat sink substrate has become significant for its dual advantage of eco-friendliness and sufficient thermal conductivity [14]. Obaid and Hameed [11] experimentally and numerically validated that heat sinks produced from recycled blocks possess equivalent thermal performance to those from virgin materials, particularly when paired with optimized fin perforation. The recycling of materials is consistent with international green production programs that restrict raw material usage and lower waste content without impairing heat dissipation efficiency [1-14].

Optimization research focuses on the interaction of perforation size, shape, pitch, and distribution to achieve optimum convective heat transfer and a minimum pressure drop [12-20]. For instance, Shaeri [15] discovered that lateral perforation arrangements perform better than straightforward direct perforations by enabling improved airflow and boundary layer disturbance. Elshafei [16] built on this by demonstrating that stacked perforations coupled with fin array design optimizations result in maximum heat dissipation in natural convection regimes. These results indicate a distinct design approach to achieving thermal improvement balanced by reduced weight and material expense.

2. Methodology

2.1 Materials and Sample Preparation

Recycled aluminum blocks were used as the input material to create heat sinks for this study. The blocks were drilled with round holes to create fin structures through a mechanical perforation process. Hole diameter, spacing, and pattern were kept the same for all the samples. Comparison testing was also conducted using standard commercially manufactured heat sinks made from conventional aluminum alloy.

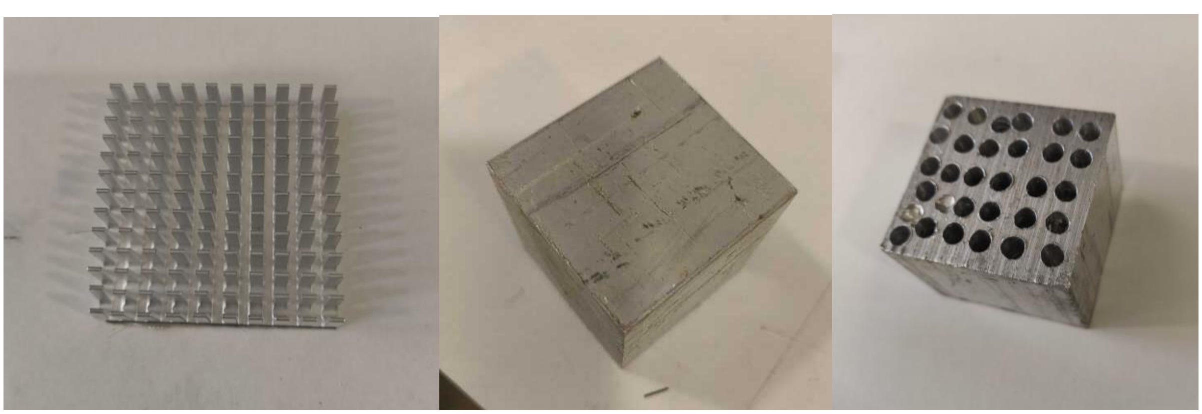

Fig 1: Standard Heat Sink Fig 2: AluminumWaste block Fig 3: Perforated aluminum block

2.2 Experimental Setup

The thermal performance of the heat sinks under natural convection conditions was tested. The experimental assembly consisted of the following elements: two 12 V Positive Temperature Coefficient (PTC) heating elements mounted on a PCB board using thermal paste. The heat sink was placed directly over the heating elements to mimic real-world heat transfer situations. The heating elements were powered and controlled using an STC-1000 temperature controller so that the surface temperature was held between 80–90 °C. Two Negative Temperature Coefficient (NTC) thermistors were positioned in strategic locations: one at the heater's base (in direct contact with the heater) and another on the top surface of the heat sink for measuring temperature gradients.

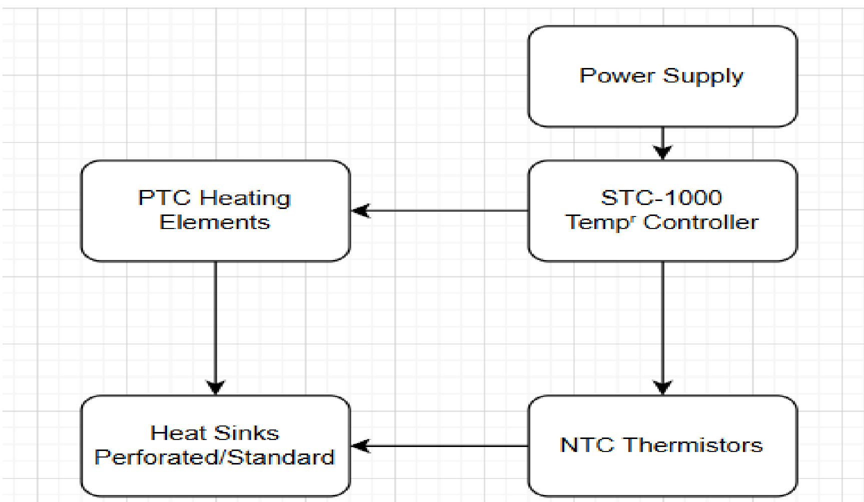

Fig 4: Block diagram of Experimental Setup

2.3 Experimental Procedure

1. The STC-1000 was switched on using a power supply with a voltage of 15V and current of 4A
2. The heating elements were allowed to reach steady-state conditions at a target temperature of approximately 80 °C, controlled via the STC-1000 controller.
3. Upon reaching this thermal equilibrium, power was automatically cut off by the STC-1000 controller, initiating the cooling phase under ambient, natural convection conditions.
4. The temperature data from the NTC sensors at the top and the base of the heat sink was collected for the entire cool-down duration (400 s).
5. The difference in temperature recorded between the top and base sensors was then used to analyze thermal transients and thermal behavior.
6. Each heating and cooling cycle was repeated for each type of heat sink (no heat sink, perforated recycled aluminum, and regular heat sink) to achieve repeatability and equivalency.

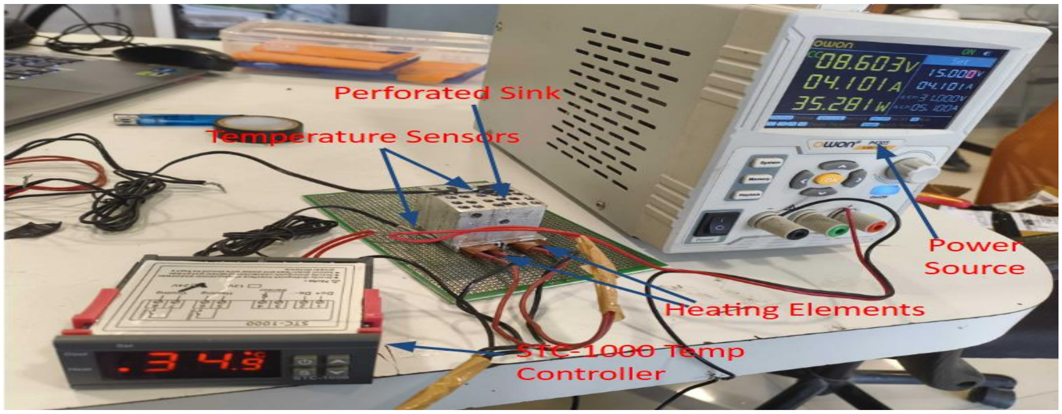

Fig 5: Schematic of the experimental setup

3. Calculations

Symbol	Description
T_b	Base temperature of heat sink (°C)
T_∞	Ambient temperature (°C)
T_i	Initial temperature (°C)
T_f	Final temperature (°C)
k	Thermal conductivity (W/m·K)
ρ	Density (kg/m³)
c_p	Specific heat capacity (J/kg·K)
h	Heat transfer coefficient (W/m²·K)
A_c	Cross-sectional area of the fin (m²)
P	Perimeter of the fin cross-section (m)
A_s	Surface area of the fin (m²)
m	Fin parameter (m⁻¹)
η	Fin efficiency
Q_{fin}	Heat dissipated by one fin (W)
Q_{total}	Total heat dissipated by all fins (W)

Table 1: Nomenclature

3.1 Geometry and Material Properties

i. Block Dimensions: 50 mm × 50 mm × 50 mm
ii. Hole Diameter: 5 mm
iii. Hole Depth: 40 mm
iv. Number of Holes: 30
v. Material: Aluminum
  - Thermal Conductivity, $k=205$ W/mK
  - Density, $\rho=2700$ kg/m^3
  - Specific Heat, $c_p=900$ J/kgK
vi. Base Temperature (T_b): 80°C
vii. Ambient Temperature ($T\infty$): 25°C
viii. Natural Convection Heat Transfer Coefficient: $h\approx10$ W/m^2·K

3.2 Fin Geometry and Heat Transfer Calculations

Each drilled hole is treated as a cylindrical pin fin:

a. **Fin Radius (r):** 0.0025 m
b. **Fin Length (L):** 0.04 m
c. **Cross-Sectional Area (A_c):** $A_c = \pi r^2 \approx 1.9635\times10^{-5}$ m^2
d. **Perimeter (P):** $P = 2\pi r \approx 0.0157$ m
e. **Surface Area of One Fin (A_s):** $A_s = P\cdot L \approx 6.28\times10^{-4}$ m^2
f. **Fin Parameter (m):** $m = \text{sqrt}\{h.P/k.A_c\} = \text{sqrt}\{10\cdot0.0157 / 205\cdot1.9635\times10^{-5}\} \approx 6.24$ m^{-1}
g. **Fin Efficiency (η):** $\eta = \tanh(mL) / mL = \tanh(0.2496) / 0.2496 \approx 0.981$
h. **Heat Loss per Fin:** $Q_{fin} = \eta\cdot h\cdot A_s\cdot(T_b-T\infty) = 0.981 \text{ x } 10\cdot6.28 \times 10^{-4} \text{ x } (80-25) \approx 0.0339$ W
i. **Total Heat Loss from All Fins:** $Q_{total} = 30\cdot Q_{fin} \approx 1.02$ W

3.3 Cooling Time Calculation

Mass of the Block: $m = \rho V \approx 0.274$ kg

Using the energy balance:
$dT / dt = -Q . m . c_p \Rightarrow t = (m.c_p / Q)\cdot\ln(T_i-T\infty / T_f-T\infty)$
Substitute:
$t = (0.274 \cdot 900 / 1.02) \cdot \ln((80-25) / (30-25)) = 241.76\cdot2.398 \approx 580$ seconds ≈ 9.7 minutes

Parameter	**Value**
Fin Efficiency (η)	98.1%
Heat Loss per Fin	0.0339 W
Total Heat Loss (30 fins)	1.02 W

Cooling Time (80°C → 30°C)	≈ 580 sec

Table 2: Summary of calculated results

3.4 Numerical Simulation

To support experimental findings, transient thermal simulations replicating the physical setup were conducted using ANSYS Workbench. Figures 4 and 5 show a detailed 3D CAD model constructed in SolidWorks of the experimental assembly, including the heating elements and PCB base, and the heat sink geometry with perforations, heating elements, and PCB base, respectively.

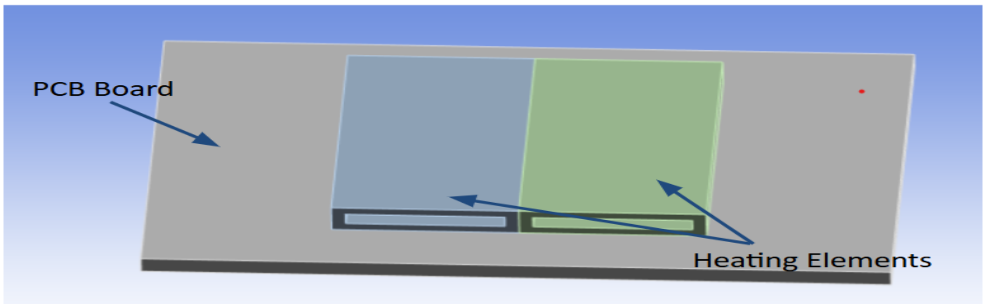

Fig 4: CAD assembly including the heating elements and PCB base

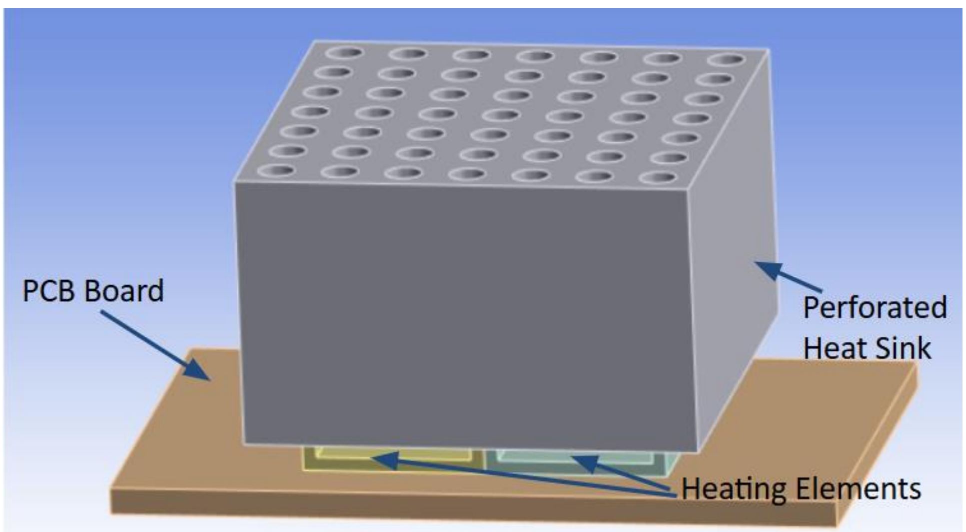

Fig 5: CAD assembly including the heat sink geometry with perforations, heating elements and PCB base

3.5 Simulation Setup

The transient thermal simulation was performed in ANSYS to investigate the cooling performance of a heat sink assembly. The geometry consisted of a cubical aluminum heat sink (50 mm × 50 mm × 50 mm) resting atop a base plate made of FR-4 material. The aluminum block had a top surface with 30 equidistant vertical holes with a diameter of 5 mm and a depth of 40 mm, which acted as extended surfaces (fins) to assist in convective heat dissipation.

A heat flux was applied to the inner surface of a heating element placed at the boundary between the base and the aluminum heat sink. The flux was calibrated to elevate the temperature of the element at a rate sufficient to increase the temperature from ambient (25 °C) to 80 °C within 40 seconds of heating. The heating cycle was modeled over 40 seconds prior to switching off the heat input to allow the system to cool naturally with ambient air (natural convection) for the remainder of the simulation (total time: 540 seconds).

Parameter	**Value**	**Unit**
Initial Ambient Temperature	25	°C
Final Temperature of Heating Zone	80	°C
Heat Flux Duration	0–40	seconds
Cooling Duration	40–540	seconds
Material of Sink Block	Aluminum	–
Material of Base Plate	FR-4	–
Sink Dimensions	50 × 50 × 50	mm
Hole Diameter (Fin)	5	mm
Hole Depth	40	mm
Number of Holes	30	–
Convective Heat Transfer Coefficient (Natural)	~10	$W/m^2 \cdot K$
Simulation Type	Transient Thermal	–

Table 3: Input parameters for ANSYS simulations

4. Results

The thermal performance of different heat dissipation scenarios was examined using both ANSYS simulated measurements and physical measurements, shown in the following figures.

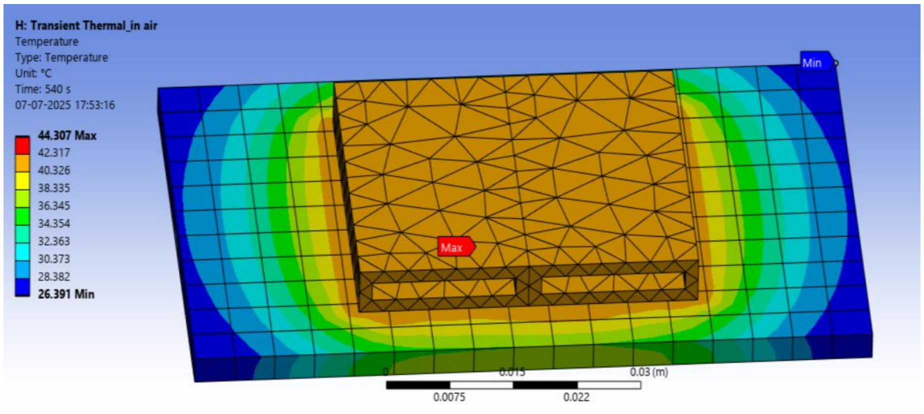

Fig 6: ANSYS transient thermal simulations for heating element under natural convection without a heat sink

After 540 seconds of exposure to heat, the temperature distribution of the heating element (without a heat sink) showed a maximum temperature of 44.3 °C around the center-bottom region, where the heating element was in contact with the base. The outside surfaces, especially the upper corners, cooled more significantly, reaching lower temperatures of 26.4 °C due to natural convection. The heat remained more concentrated around the core for a longer period because the surface area for convective dissipation was lower. The lack of extended surfaces also limited the heat transfer efficiency, particularly during cooling.

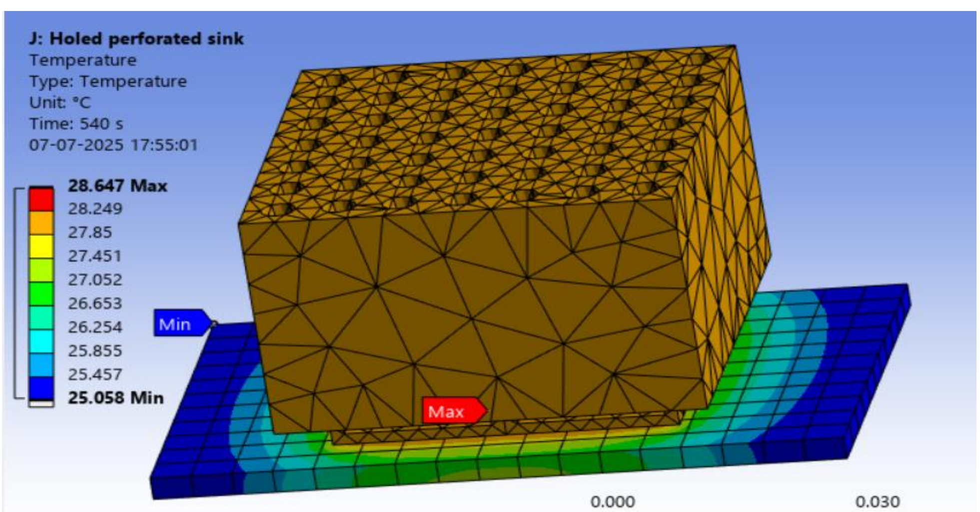

Fig 7: ANSYS transient thermal simulations for heating element mounted with a perforated heat sink under natural convection

With the addition of a perforated heat sink (acting as fins), the maximum temperature achieved at 540 seconds was noticeably lower at 28.6 °C, while the minimum temperature dropped to 25.1 °C. The perforations improved air circulation through the structure and increased the surface area for natural convective cooling. Compared to the solid sink, the perforated geometry showed a more consistent distribution of surface temperature gradients and more rapid cooling over the same period of time. Overall, the results indicated that adding fin-like geometries can improve passive thermal performance.

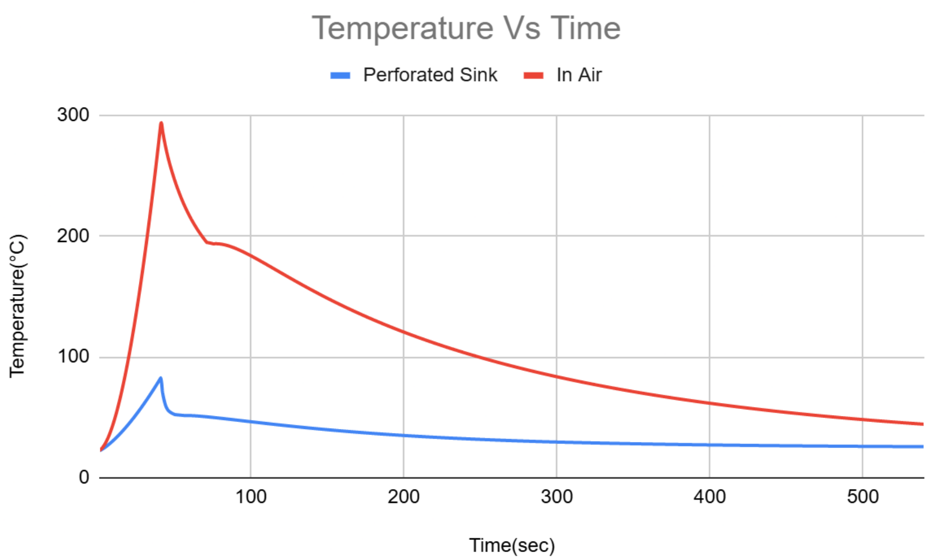

Fig 8: ANSYS results for heating element with and without a perforated heat sink under natural convection The heating element in air heated up very quickly and reached a maximum temperature of nearly 290 °C after 60 seconds. It then started to cool, but the cooling period was gradual, indicating that heat dissipation is very poor without a heat sink. The perforated heat sink maintained a peak temperature reduction of ~90 °C, with a significantly better-controlled cooling curve. The perforated heat sink also demonstrated improved heat transfer via natural convection; the increase in convection and surface area provided by the perforations enabled it to reduce temperature more efficiently than the solid heat sink without perforations. The experiments suggest that adding perforations to the heat sink significantly improves the ability to cool passively by natural convection. The perforated heat sink cooled to a peak temperature approximately 15.7 °C lower than the solid heat sink configuration after 540 seconds of cooling. These findings confirm the fin analogy for internal perforations and highlight the effectiveness of surface area enhancement strategies in thermal management systems.

The experimental results are given below:

The heating element is powered on to reach temperature 80^0C and their time is noted then the power is auto cut by SCT-1000 temperature controller, once the power is cutoff the heating element overshoots to a certain temperature as given is Table 1 then starts to cooldown. Then cooldown temperature and time is noted for the heating element surface.

The readings for heating element without heat sink are as follows:

Reading Number	Cutoff Temp (^{0}C)	Cutoff Time(sec)	Overshoot Temp(^{0}C)	Cooldown Temp(^{0}C)	Cooldown Time(sec)	Temp Differ(^{0}C)
1	90	103	95	40	160	55
2	90	60	99.5	45	420	54.5
3	90	42	99.5	45	400	54.5
4	90	33	109	45	420	64
5	90	30	92	45	364	47
6	80	24	89.7	50	158	39.7
7	80	32	88.7	50	218	38.7
8	80	38	87.4	50	225	37.4
9	80	35	88.4	50	225	38.4
10	80	36	88.3	50	223	38.3

Table 3: Experimental reading for heating element without heat sink. Natural convection in air

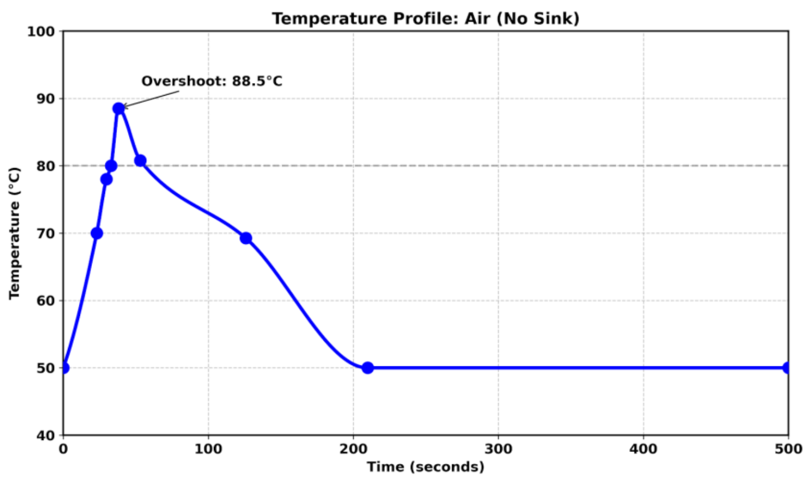

Fig 9: Plot results for heating element temperature change w.r.t. time

4.1 Base Only (No Heat Sink)

- Temperature Profile: The temperature remained highly elevated in the heated area during cooling, demonstrating ineffective heat dissipation.
- Peak Temperature: After 540 seconds, the highest temperature attained was around 44.3 °C, and the lowest temperature was about 26.4 °C.
- Thermal Gradient: A rapid thermal gradient was identified along the base, indicating limited heat distribution and reduced conductive and convective heat loss.
- Convection Limitation: Minimal exposed surface area was a definite factor for the effectiveness of heat loss via natural convection.

The readings for Standard heat sink are as follows:

Readin	Cutoff	Cut	Cutoff	Overshoot	Overshoot	Cooldow	Cooldown	Cool	Tem

g Number	Temp(^{0}C)	off Time(sec)	Temp(Sink Top)	Temp(^{0}C)	Temp(Sink Top)(^{0}C)	n Temp(Sink Top)(^{0}C)	Temp(Element)(^{0}C)	down Time (sec)	p Differ(^{0}C)
1	80	34	45	88.3	55	42	45	394	43.3
2	80	36	37	86	55	41	45	407	41
3	80	60	45	88.6	57	41	45	462	43.6
4	80	51	46	89	56	41	45	448	44
5	80	28	47	88	57	42	45	531	43
6	80	42	46.5	81.3	80.4	50.7	50	219	31.3
7	80	48	75.8	81.7	80.2	50.5	50	224	31.7
8	80	46	75.1	81.9	80.2	50.3	50	224	31.9
9	80	49	75.5	81.5	79.7	50.2	50	224	31.5
10	80	49	75.1	81.1	78.9	50.3	50	230	31.1

Table 4: Experimental reading for Standard heat sink under natural convection

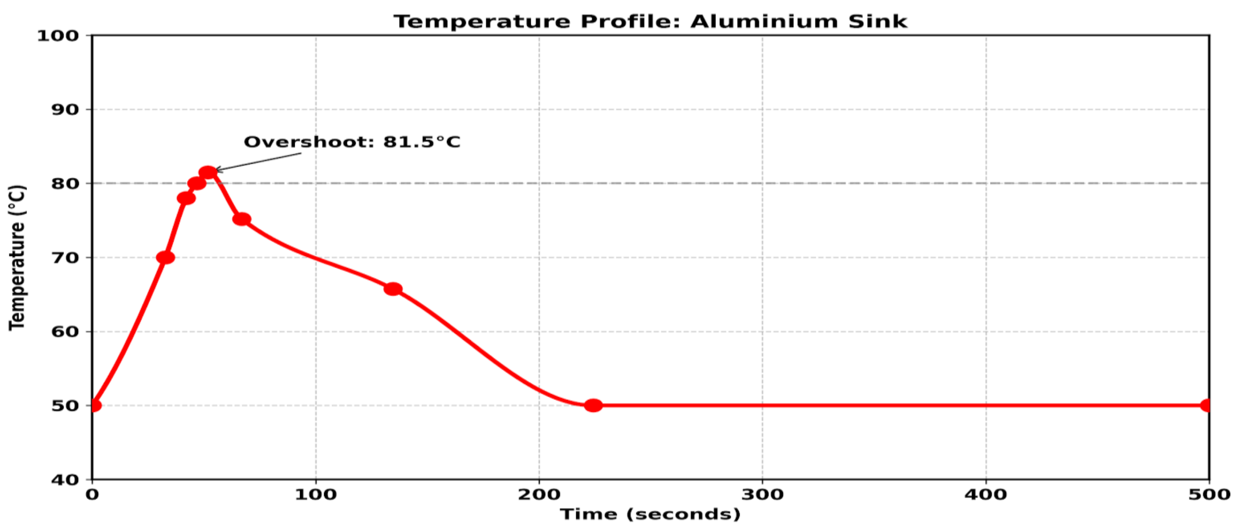

Fig 10 : Plot results for heating element with Standard heat sink temperature change w.r.t. time

4.2 Standard Aluminium Heat Sink

I. Temperature Distribution: Overall, the solid heat sink resulted in more consistency across the block, as the temperature drop was more gradual and distributed compared to the base-only study.

II. Maximum Temperature: The maximum temperature measured was 28.6 °C and the lowest temperature was 25.1 °C at the outer region.

III. Better Conduction: The block did provide a significant amount of thermal conductivity to distribute heat more efficiently through the volume.

IV. Convection Limitation: Even with the better conduction ability of the block, the total rate of convective cooling was limited because of the reduced or non-extended surface area.

The readings for Perforated heat sink are as follows:

Reading Number	Cutoff Temp(^{0}C)	Cutoff Time(sec)	Cutoff Temp(Sink Top)(^{0}C)	Overshoot Temp(^{0}C)	Overshoot Temp(Sink Top)(^{0}C)	Cooldown Temp(Sink Top)(^{0}C)	Cool down Temp(Element)(^{0}C)	Cool down Time(sec)	Temp Differ (^{0}C)
1	80	40	53.5	81.8	54.3	52.9	45	262	36.8
2	80	42	53.6	81.8	54.2	52.7	45	263	36.8
3	80	42	53.4	81.7	53.8	53.3	45	254	36.7
4	80	39	53.8	81.8	54.2	52	45	293	36.8
5	80	42	52.7	81.6	53.1	53.5	45	254	36.6
6	80	116	78.4	82.5	82.1	56.4	55	575	27.5
7	80	102	78.2	82.7	81.8	56.3	55	565	27.7
8	80	102	78.1	82.7	81.8	56.2	55	570	27.7
9	80	100	77.7	82.7	81.2	56.1	55	556	27.7
10	80	101	77.3	82.7	80.9	56	55	563	27.7

Table 5: Experimental reading for perforated heat sink under natural convection

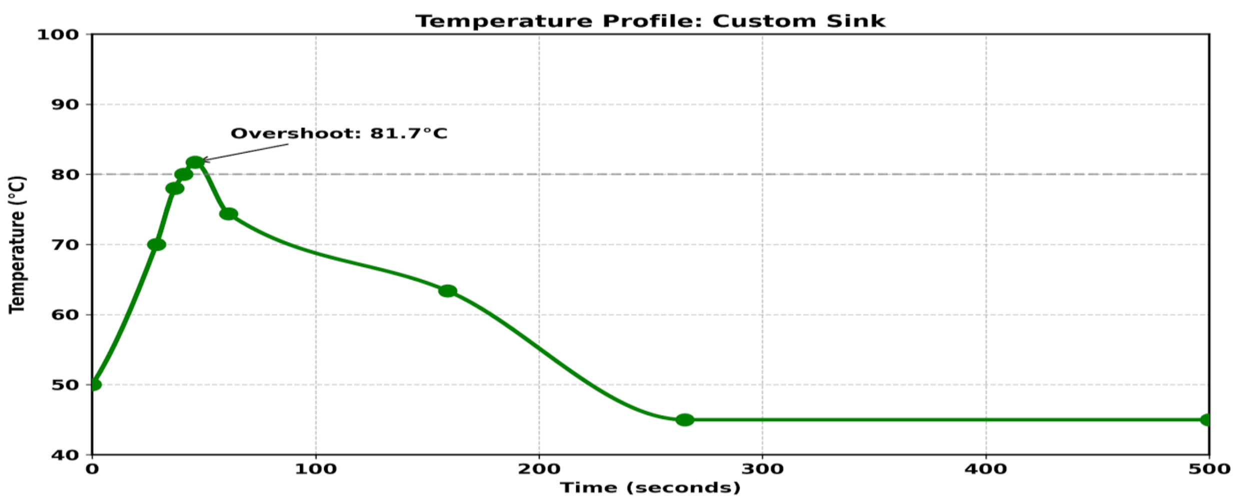

Fig 9 : Plot results for heating element with perforated heat sink temperature change w.r.t. time

4.3 Perforated Aluminium Heat Sink

A. **Temperature Distribution:** Specifically, the perforations not only enhanced temperature uniformity, but also reduced the magnitude of hotspots across the heat sink.

B. **Maximum Temperature:** The perforated configuration retained lower temperatures across the testing conditions as more outer surface area, within the heat sink, was exposed to ambient air and higher cooling rates.

C. Improved Surface Area: The 30 perforated holes introduced internal surfaces, which provided further natural convection routes into and out of the heat sink. The exposed, outer surfaces, additionally helped to dissipate heat externally from the heat sink along with heat dissipating from inside the sink, effectively giving the heat more surfaces to radiate or convect heat from.

D. The most effective cooling: The perforated configuration was able to initially lower temperature the fastest and have the closest operational temperatures to ambient conditions during the full cooling duration.
E. Air movement: It is possible the perforated holes produced a mild dispersion airflow within the perforated structure that contributed to greater rates of natural heat transfer.

5. Conclusion

This study investigated the thermal behavior of recycled aluminum block heat sinks, with emphasis on the role of internal perforations in natural convection mode. ANSYS simulations and experimental tests presented similar trends verifying the validity of the findings observed in the study. The control case, a heating source that was running without the presence of any heat sink experienced dramatic temperature accumulation and dissipation behavior. Short heat loss times with low steady-state temperatures and fast cooldown times were caused by the lack of long surfaces and minimal surface convective area. However, the conventional aluminum heat sink enhanced heat spreading because of the extremely high thermal conductivity of aluminum. Although this design lowered peak temperatures and prolonged the cooldown time compared to the base only situation, the performance was comparative to the custom heat sink. The internally perforated aluminum heat sink from drilled recycled cast blocks significantly surpassed the base only and showed closer results to that of the conventional heat sink. Incorporation of the internal cylindrical perforations not only enhanced the effective surface area but also facilitated passive airflow through the structure, thereby enhancing natural convection. The design had the lowest peak temperatures for the entire heating cycle, greatest rate of cooldown, and most symmetrical temperature profile along the surface of the heat sink.

These findings support the hypothesis that internal perforations are similar to fins, with considerable active thermal enhancement using very little material or weight addition. Also, the successful incorporation of recycled aluminum cast blocks proves the ability of green material practices in thermal management systems, particularly for passive or low-power electronics applications.

In short, perforated heat sinks provide a cost-effective, eco-friendly, and high thermal performance improvement solution. Even further optimization of the design by adjusting hole diameter, spacing, and orientation can be utilized to tailor cooling performance for particular applications, where they are a good candidate for next-generation heat dissipation technologies.

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