Thermoelectric Cooler with Different Fins Configuration

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Abstract

Thermoelectric coolers are solid-state devices that use the Peltier effect to convert electrical energy into a temperature gradient, cooling one side and heating the other. Their main advantages are compact size, absence of moving parts, and low noise emissions. However, the low-performance coefficient of thermoelectric coolers is a significant limitation. Regarding the fins design, comparative analysis for the plate-fin heat sink with cross-fin showed improvements in both overall and convective heat transfer coefficients for the cross-fin design, registering increases of 11% and 15%, respectively. It is also stated that the perforated pin configuration demonstrates the highest heat transfer coefficient at 89.50 W/m²K, followed by the perforated flat plate at 87.60 W/m²K and the solid pin-fins at 82.60 W/m²K. Conversely, the solid flat plate exhibits the lowest heat transfer coefficient at 82.40 W/m²K. This indicates that conventional designs have relatively low heat transfer coefficients, indicating a need for further investigation and the application of new designs. While some studies have examined individual design factors, research on their combined effects on system performance is limited. Additionally, there is a lack of research on optimizing heat sink designs, particularly concerning fin types and shapes in thermoelectric coolers. This gap hinders our ability to optimize thermoelectric cooler designs for maximum efficiency and effectiveness in real-world applications. This study aims to determine the performance optimization of thermoelectric coolers by analysing the impact of various design parameters such as fin shapes and different designs, airspeed, and current on their efficiency and effectiveness.

1. Introduction

Thermoelectric coolers have the potential to dominate traditional air conditioning systems and become the future of HVAC (Heating, Ventilation, and Air Conditioning). Thermoelectric coolers offer zero greenhouse gas emissions, a leak-free environment, and cost efficiency [1]. The average global temperature has been increasing, and air-conditioning and refrigeration systems contribute to a significant portion of the world's electrical energy demand. Conventional systems rely on fossil fuels, leading to CO_2 emissions. Thermoelectric coolers, working on the principle of the Peltier effect, are an alternative solution. In contrast, the Peltier Effect is defined as the phenomenon where passing an electric current through two dissimilar conductors can absorb or release heat at the junction, depending on the direction of the current. They are refrigerant-free, produce no noise or vibration, and can be directly powered by solar photovoltaic systems [2]. Conventional refrigeration processes release coolants or refrigerants into the atmosphere, contributing to global warming.
On the other hand, thermoelectric coolers do not require coolants or refrigerants and can be used in various applications [3]. Thermoelectric coolers are suitable for addressing greenhouse emissions in

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cooling scenarios due to their noise-free and chemical-free operation. They find applications in smart cities, greenhouses, and thermal management of personal devices and chips [4]. However, thermoelectric coolers are associated with drawbacks and challenges, with a notable limitation being their low coefficient of performance, coefficient of performance (COP), which is defined as a ratio that measures the efficiency of a thermoelectric cooler, calculated as the heat removed per unit of electrical energy used. This drawback hinders their overall energy efficiency and effectiveness compared to conventional cooling methods. Addressing this limitation is crucial for enhancing the practical utility of thermoelectric coolers in diverse thermal management applications. This study presents the state-of-the-art thermoelectric coolers' performance through different design parameters, including fin shapes (Plate fins – Pin fins – Perforated fins), airspeed, and current. The impact of heat sink geometry on system performance is crucial, shedding light on the need for efficient design choices. In contrast, the heat sink is a device or substance for absorbing excessive or unwanted heat. Now that we've explored the potential of thermoelectric coolers and discussed their advantages and challenges let's look at how this paper is organized. In the following sections, we will delve into a comprehensive review of existing literature on thermoelectric coolers, followed by conclusions for our research. We will then present and discuss the findings and future recommendations regarding thermoelectric coolers' performance across different design parameters.

2. Literature Review

2.1 Plate Heat Sink

This section delves into the literature on optimizing plate-fin heat sinks, emphasizing design parameters such as fin shapes, thickness, and spacing. The plate-fin heat sink is one of the most widely accepted heat sinks for its simple geometry and low cost. Elenbaas [5] led the way for a detailed examination of heat transfer from vertical plate-fin heat sinks, serving as a cornerstone for subsequent studies in the domain. Wong et al. [6] indicated that plate fins represent the optimal choice among various options, including fins, blades, and circular pins. Silva et al. [7] used an analysis of variance (ANOVA). The variables' impact and interactions on various plate heat sinks were assessed to understand their effects on each response (Figure 1). The study also indicates that minimizing fin thickness is crucial, whether aiming for a reduced sink temperature (as depicted in Figure 2, top) or a lower pressure drop (illustrated in Figure 2, bottom). Interestingly, this principle does not hold for fin spacing. On the one hand, minimal spacing enhances the fin density, consequently improving thermal efficiency. Conversely, reducing spacing results in higher pressure drops [7]. Silva et al. study [7] revealed that introducing fillets or chamfers yielded no advantages in the heat sink design. Instead, the investigation considered fins with trapezoidal and inverted trapezoidal shapes (as depicted in Figure 1B).

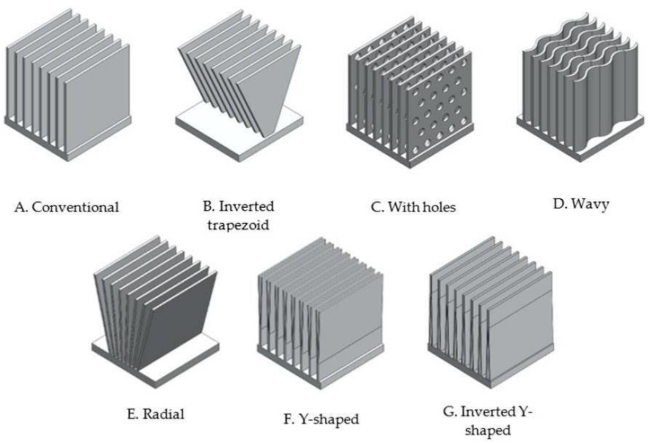


Fig. 1: Different plate heat sink models [7].

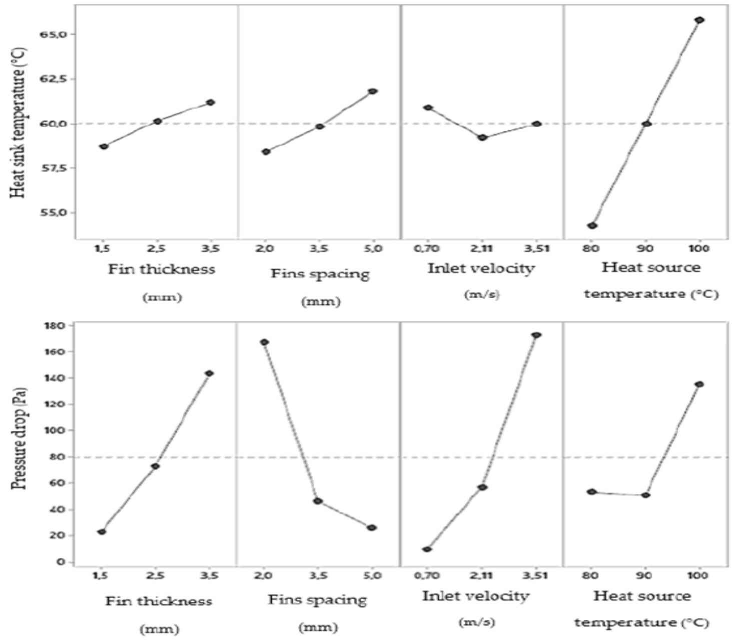
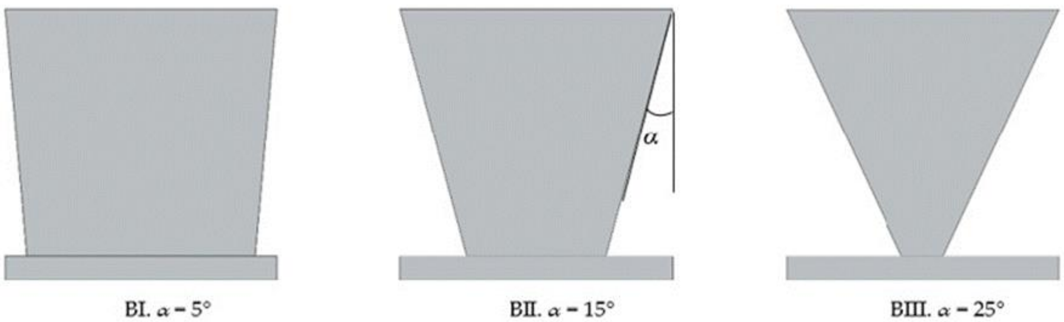


Fig. 2: Main effects for heat sink temperature (top) and pressure drop (bottom) for the fins heat sink. [7].



Model	Total area (cm^2)	Front area (cm^2)	Volume (cm^3)	HS temperature after 15 sec (°C)	Pressure drop (Pa)
BI	380.9	7.7	36.4	56.1	15.4
BII	323.5	7.7	31.9	50.7	16.5
BIII	260.7	7.7	27.0	40.0	15.9

Fig. 3: Model B variants [7]

The inverted trapezoidal shape was advantageous due to its broader section exposed to ambient air. Furthermore, the study noted that an increase in the inverted trapezoid angle correlated with improved performance (Figure 2.3).

Charles and Wang [8] conducted experiments comparing triangular and trapezoidal fins, revealing notable findings. The results demonstrated a remarkable improvement of over 20% in the inverted trapezoidal fin configuration. This design exhibited superior performance compared to trapezoidal fins, attributed to natural convection heat transfer decreasing with an increase in fin length while remaining insensitive to fin thickness and height changes.

Jeon and Byon [9] numerically investigated the thermal performance of plate-fin heat sinks with a dual-height fin profile, considering fin spacing and channel length under natural convection. The findings indicated a consistent decrease in the thermal performance of the dual-height heat sink as the secondary fin height decreased for a constant primary fin height. Nevertheless, there is a potential enhancement in the thermal performance per unit mass by reducing the secondary fin height. This implies that the dual-height heat sink could be a viable option for diverse practical applications where the heat sink's mass plays a crucial role in determining product value. Additionally, it is demonstrated that a critical threshold exists for the primary fin height. Below this threshold, the thermal performance of the dual-height heat sink experiences a decline as the secondary fin height decreases. Notably, this threshold value exhibits a linear decrease with increased channel length. Shangsheng et al. [10] introduced and validated a pioneering cross-fin heat sink design to enhance natural convective heat transfer.

The research conducted numerical simulations considering natural convection and radiation heat transfer. The dimensions of the reference plate-fin heat sinks are illustrated (as shown in Figure 4). Two heat sinks were used: cross-fin and conventional plate-fin heat sinks. In contrast, the cross-fin heat sink exhibited a more favourable scenario. Cold air reached the shortfin channel, forming an impinging-like flow toward the end wall. This characteristic proved beneficial for enhancing heat transfer. Comparative analysis with the plate-fin heat sink revealed notable improvements in both overall and convective heat transfer coefficients for the cross-fin design, registering increases of 11% and 15%, respectively.

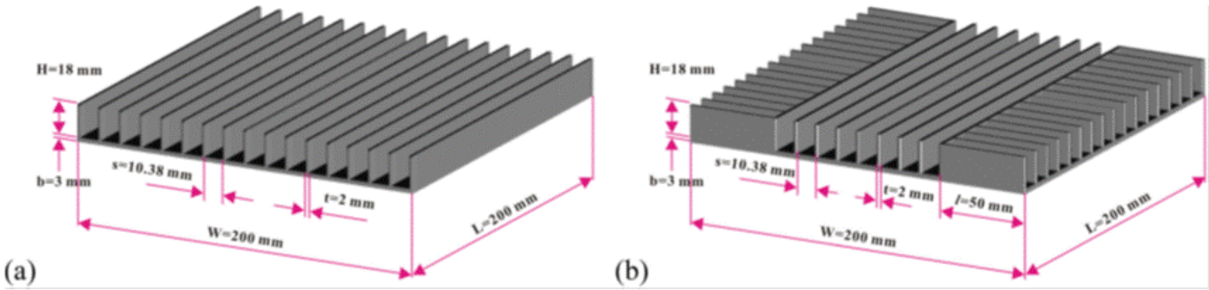


Fig. 4: Schematic of (a) conventional plate-fin heat sink and (b) proposed cross-fin heat sink [10].

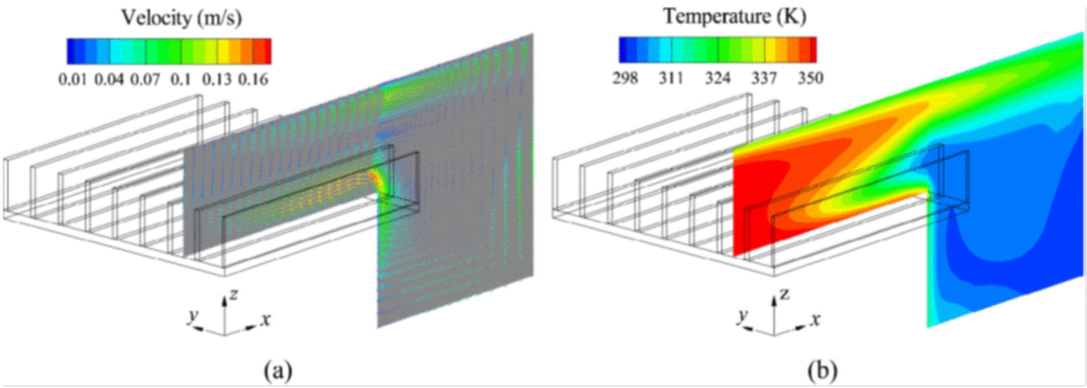


Fig. 5: Thermal and fluid-flow distributions in plate-fin heat sink: (a) velocity field in a fin channel; (b) temperature field in the same fin channel [10]

We observe a cross-section's temperature distribution at the fin channel's midpoint within the plate-fin heat sink [Figure 5 (b)]. The data indicates that fresh cold air can only penetrate the channel from the entrance a limited distance [as depicted in the velocity distribution of Figure 5, (a)]. A high-temperature zone near the channel center implies inefficient heat transfer in that specific region. To summarize, these results underscore a noteworthy limitation of the traditional plate-fin heat sink: it impedes the smooth flow of cold air toward the center of the fin channels, impacting overall heat transfer efficiency [10].

However, to address, at least partially, the shortcomings of traditional plate fins, the cross-fin heat sink introduces a novel design by segmenting fins into two categories: long fins and short fins (as illustrated in Figure 4(b)). Examining the velocity and temperature distributions in a cross-section aligning with the midpoint of a long fin channel [as shown in Figure 6 (a) and (b)] and similarly for a short fin channel [as shown in Figure 6 (c) and (d)], exciting observations emerge. Figures 6 (a) and (b) indicate that the velocity and temperature patterns in the long channel of the cross-fin heat sink closely resemble those in a plate-fin heat sink. However, intriguingly, fresh air permeates the entire fin channel for the short fins [as shown in Figures 6 (c) and (d)]. This leads to a higher average heat transfer rate on the short fins than on the long fins. Additionally, [as illustrated in Figure 6, (c)], the flow entering the shortfin channel eventually impinges toward the end wall of the channel, specifically the long fin that intersects with the short fins. These findings highlight the innovative design's ability to facilitate improved airflow and heat transfer, particularly in the context of the shorter fins [10]. In the context of plate-fin heat sinks, the simulation results indicated a limitation in the penetration of cold air into the fin channel from the entrance. This phenomenon resulted in inferior thermal efficiency, particularly at the center of the heat sink [10]. Kim [11] indicated that modifying fin thickness in the direction perpendicular to fluid flow could be a promising strategy for minimizing heat resistance in natural convection heat sinks. This approach parallels successful tactics employed in forced convection heat sinks, where increasing fin thickness has demonstrated effectiveness in enhancing the overall thermal performance of the system.

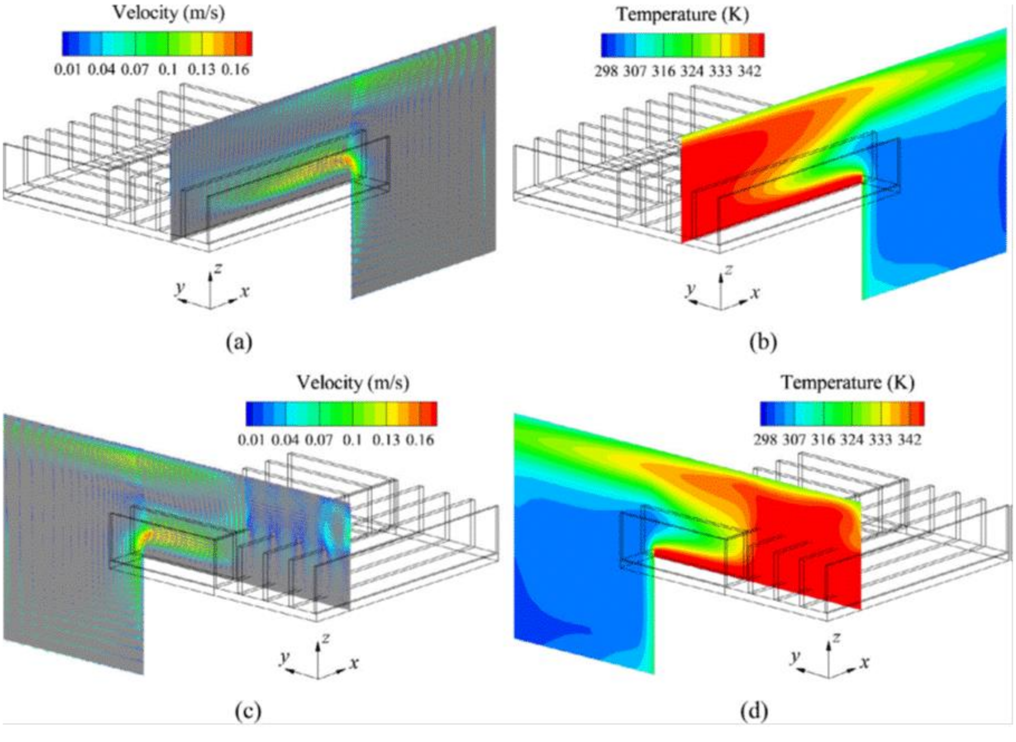


Fig. 6: Thermal and fluid-flow distributions in cross-fin heat sink: (a) velocity field in a long fin channel; (b) temperature field in the same long fin channel; (c) velocity field in a short fin channel; (d) temperature field in the same short fin channel [10].

2.2. Pin Heat Sinks

Examining pin-fin heat sinks, Wong⇑ and Indran [12] conducted a numerical demonstration highlighting the advantages of incorporating fillet profiles at the bottom of plate fins in a multichannel heat sink. The outcomes affirm that introducing a fillet profile significantly improves heat transfer performance compared to the conventional design, which lacks a fillet (rectangular channel without fillet). This enhancement in thermal performance reaches 13% under the investigated conditions. The results indicate that larger fillet radii correspond to better heat transfer performance. Jaffal [13] conducted a comprehensive analysis of the thermal performance of various fin heat sink geometries through a combination of experimental and computational studies, focusing on a specific heat flux interval. The findings revealed a consistent trend across all heat sinks, indicating a reduction in thermal resistance with an increase in heat flux. This phenomenon is attributed to the heightened heat transfer between the heat sink and the surrounding air. Ibrahim et al. [14] employed simulations in ANSYS software to explore the impact of perforation geometry (circular, rectangular, and triangular) on the heat transfer characteristics of perforated fin heat sinks under various boundary conditions. The results consistently indicated that the presence of perforations led to an increase in the heat transfer coefficient and a decrease in heat sink temperature, irrespective of the specific perforation geometry employed. Al-Sallami et al. [15] delved into the advantages of employing strip fin heat sinks with cross-sectional aspect ratios falling between those of plate fins (high aspect ratio) and pin fins (aspect ratio ≈ 1). The exploration was conducted computationally, utilizing a conjugate heat transfer model. The utilization of strip fins with varying cross-sectional aspect ratios was considered. Strip fins have proven to be highly effective in disrupting the boundary layer.

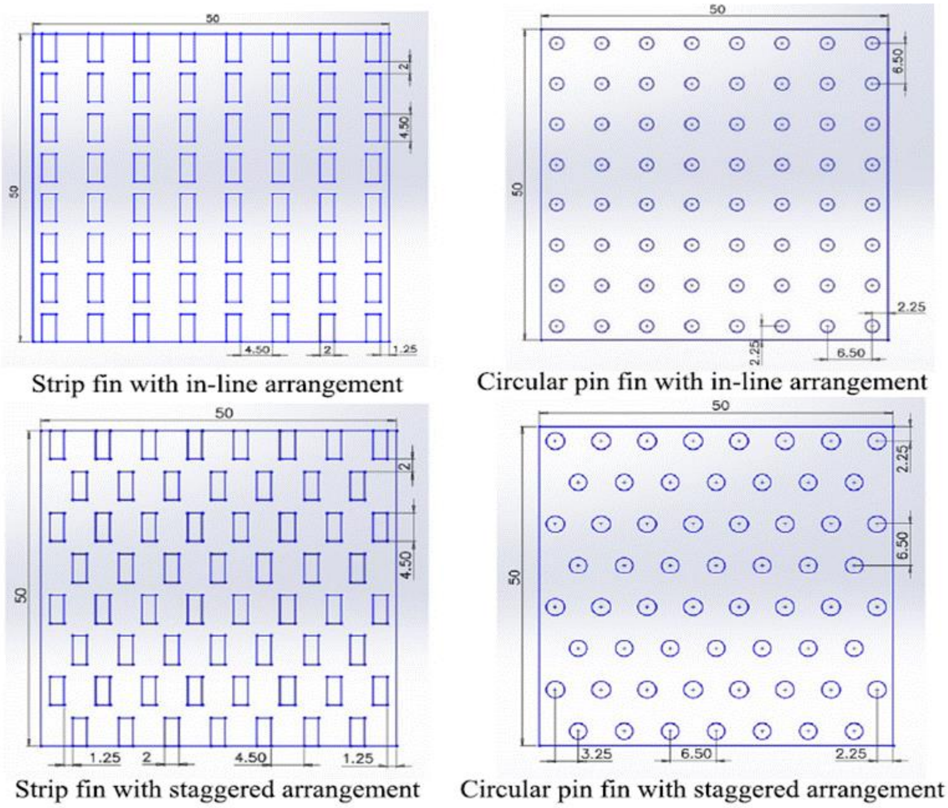


Fig. 7: Schematic diagram of different heat sink geometries and arrangements [15].

. The augmented fin-wetted surface area and increased turbulence can significantly improve heat transfer, albeit with associated higher pressure losses. The arrangement of strip fins in a staggered configuration further enhances heat transfer, albeit at the cost of increased pressure losses. The study investigates heat sinks incorporating solid and perforated fins arranged in a line or a staggered fashion (as illustrated in Figure 7). Figure 8 illustrates the temperature distribution on solid and perforated strip fin heat sinks, comparing fins' inline and staggered arrangements. The lowest base temperature,

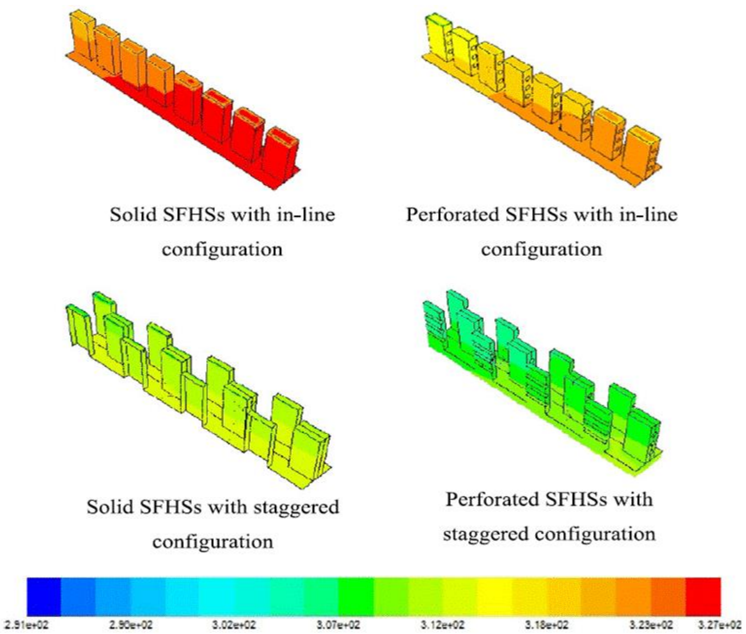


Fig. 8: Temperature distribution on solid and perforated strip fin heat sinks [15].

represented by the lightest shade of green, is achieved with the perforated strip fin heat sinks in a staggered configuration. The figure demonstrates clearly that the perforated cases have the lowest surface temperature for a given fin arrangement. Ismail et al. [16] illustrated the impact of longitudinal perforation geometry on the thermal performance of heat sinks with an identical heat transfer surface area, comparing them to regular solid fins. Their findings indicate that perforations contribute to an increased thermal performance of heat sinks, particularly under turbulent flow conditions. The specific geometry of the perforations plays a crucial role in enhancing the thermal performance of the heat sinks. Among the investigated types, circular perforated fins exhibit a higher fin effectiveness value for the same surface area. Introducing perforations leads to a notable reduction in drag force, resulting in an overall decrease in total drag force.

Consequently, perforated fins demand less cooling power (fan) than regular solid fins. Additionally, the shape of the perforation is a significant factor influencing fluid dynamic performance, with circular perforated fins exhibiting lower drag than other perforation types, as revealed by the study. Jonsson and Moshfegh [17] tested various heat sink models by analysing Reynolds numbers within the range of 3350 to 13,400 through ANSYS Fluent software. Their study concluded that utilizing pin heat sinks at higher Reynolds numbers is not advantageous. This is because pin fin heat sinks exhibit more significant pressure drops than other heat sink types under these conditions.

2.3 Perforated Heat Sinks

Dedicated to perforated heat sinks, Shaeri and Jen [18] investigate the impact of perforation sizes on the laminar heat transfer characteristics of an array of perforated fins. The research delves into crucial parameters such as pressure drop, temperature distribution, and perforation levels, aiming to enhance our understanding of their effects on the thermal performance of heat sinks. One significant contribution of the study is the introduction of the perforated fin effectiveness (PFE) parameter. This parameter illustrates the increased heat transfer rate from individual perforated fins compared to their solid counterparts. The consistently positive values of perforated fin effectiveness highlight the advantages of using perforated fins, indicating heightened heat transfer rates. The study reveals that at low Reynolds numbers, the performance of perforated fins resembles that of solid fins. However, as Reynolds numbers increase and more perforations are introduced, there is a substantial enhancement in the heat transfer rate [18]. A vital aspect emphasized in the study is the reduction in fin weight achieved by employing perforated fins. This reduction ensures material savings for fins and related equipment like heat sinks. The results indicate the practical achievement of optimization goals for low Reynolds numbers and the accomplishment of both goals for higher Reynolds numbers [18]. The perforations, resembling channels, traverse the length of the fins. A visual representation of various fin array configurations and the cross-section of perforations is provided (as illustrated in Figure 9). Notably, the fin in Figure 9e showcases the highest number of perforations (porosity) and an enhanced heat transfer rate [18].

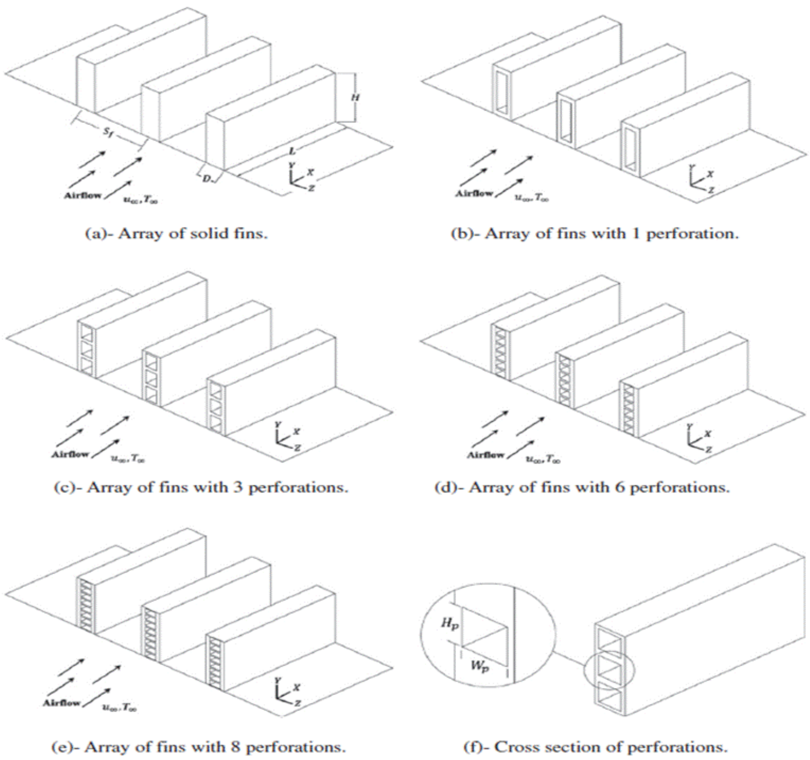


Fig. 9: Configuration of fin array [18].

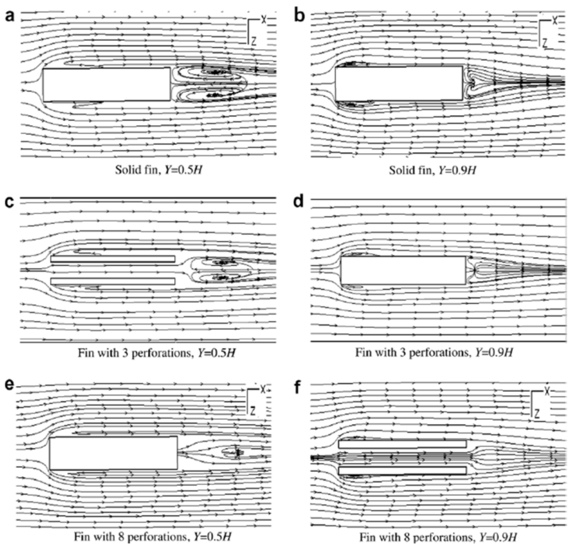


Fig. 10: Fluid path lines at different sections of fins [18].

Another layer is added to the analysis by illustrating fluid streamlines around solid and perforated fins at different heights, as illustrated in Figure 10). It underscores the symmetrical flow for solid and perforated fins and decreased recirculation region from the top to the fin base. Additionally, the length of the wake behind the fin decreases with an increase in height. For perforated fins, the flow across perforations results in the formed wake's distinct shape and size compared to a solid fin.
Al-Damook et al. [19] conducted an experimental and computational investigation of thermal air flows through perforated pin heat sinks. The study explores the advantages of employing numerous pin perforations to enhance heat transfer while concurrently reducing the pressure drop across the heat sink and the fan power required for air circulation. The Nusselt number, a key parameter in heat transfer analysis, consistently increases with an escalating number of pin perforations. This observation suggests that introducing more perforations leads to improved heat transfer characteristics. Notably, the study notes that pins featuring five perforations demonstrate a Nusselt number and pressure drop that are typically 11% and 16% larger, respectively, compared to heat sinks equipped with solid pins. Tijani's [20] work focuses on the thermal analysis of perforated pin-fin heat sinks under forced convection conditions. The study aims to understand the dependence of the heat transfer coefficient on perforation and Reynolds number for all models considered. The effect of perforation on wall heat transfer for all CATIA models of the heat sink is illustrated (as shown in Figure 11). The distinct geometries presented in the figure reveal varying heat transfer coefficients. The data suggests a correlation between increased convective surface area and enhanced heat transfer. Notably, the perforated pin configuration demonstrates the highest heat transfer coefficient at 89.50 W/m²K, followed by the perforated flat plate at 87.60 W/m²K and the solid pin-fins at 82.60 W/m²K.

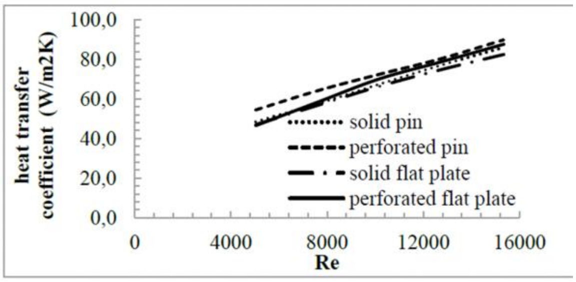
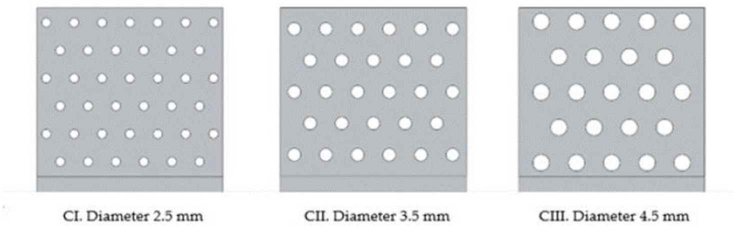


Fig. 11: The effect of the perforation on wall heat transfer for all CATIA models of the heat sink [20].

Conversely, the solid flat plate exhibits the lowest heat transfer coefficient at 82.40 W/m²K, attributed to its thin thickness limiting conductive heat transfer from the base to the fin. A significant finding of the study is the superior performance of the perforated pin fin heat sink, exhibiting a smaller pressure drop compared to its solid pin fin counterpart [20].



Model	Total area (cm²)	Front area (cm²)	Volume (cm³)	HS temperature after 15 sec (°C)	Pressure drop (Pa)
CI	415.0	7.7	36.3	54.8	17.9
CII	402.8	7.7	35.3	53.6	18.6
CIII	389.4	7.7	34.2	52.4	18.6

Fig. 12: Model variants [7].

Pontes et al. [7] evaluated active heat sink designs under forced convection conditions, focusing on the effect of geometric and boundary parameters. The study recognizes the advantages of incorporating holes in fins, attributing them to a higher heat transfer coefficient. A noteworthy observation from the study is that for larger hole diameters, maintaining consistent hole spacing results in improved heat sink performance. A model variant is presented (as illustrated in Figure 12), emphasizing the importance of geometric considerations in optimizing heat sink design.

In conclusion, the literature reviewed indicates a consensus on incorporating perforations in heat sinks. These advantages include increased heat transfer rates and improved thermal performance. Notably, geometric factors and the arrangement of perforations play a crucial role in achieving optimal heat sink performance, as demonstrated by the various studies discussed. The ongoing exploration of perforated heat sinks provides valuable insights for future advancements in thermal management systems.

2.4 Optimal Current and Cooling Capacity

Jeong [21] suggested that the ideal current increases with higher cooling capacity and decreases as the temperature difference between the hot and cold sides decreases.

Gong et al. [22] reported that the influence of electrical current concluded that when the chip was added to act as a thermal load, the upper end of the module would be exposed to significant thermal stresses near the chip. Specifically, the smaller the introduced current, the higher the thermal stress, which was more likely to cause device failure. Kolber et al. [23] concluded that the increase in the power supply value decreased its efficiency. This resulted mainly from increased Joule's heat emitted, which depends on the Peltier module's current supply square. Another phenomenon that negatively impacts the cooling cell's efficiency is thermal conductivity, which becomes more significant as the temperature difference between the hot and cold sides increases. Gao et al. [24] studied the transient supercooling characteristics of two-stage Thermoelectric Coolers (TECs) using separate current pulse operations. The research aimed to optimize the combination of pulse amplitude, pulse width, and starting time on the TEC's cold and hot stages. Key objectives included applying pulse currents to enhance the temperature drop, matching pulse amplitude and width on both stages and triggering pulse currents earlier. The methodology involved a transient TEC model with a cold and hot stage stacked together, employing different current pulse applications. The study compared single- and two-stage TECs using step current pulses, with the latter having separate current controls for each stage. Various pulse amplitudes were applied in trials, and the timing of pulse currents to the hot and cold stages was analyzed. The two-stage TEC model comprised p-type and n-type semiconductor legs with metallic connectors and ceramic plates. Conclusions revealed that the two-stage TEC with simultaneous current pulses yielded a lower cold end temperature and longer supercooling duration than single-stage TECs. Simultaneous pulses on both stages were the most effective, resulting in the lowest cold end temperature. The study emphasized the dominant role of the cold stage current pulse in reducing the minimum temperature and suggested optimal parameters for achieving better supercooling characteristics [24]. Dongcai et al. [25] highlighted the importance of selecting an optimal current that achieves larger cooling capacity, and it was noted that the lower the liquid flow rate through the heat exchanger in the TEC-HX system, the fewer TE modules and less power are required. The study focused on how different current values impact the performance of thermoelectric systems, providing insights for practical applications and design considerations.

2.5 Airflow Direction and Flow Rate

Mirmanto et al. [26] conducted a comparative study on the performance of a thermoelectric cooler box measuring 285 mm x 245 mm x 200 mm and constructed from Styrofoam using two different heat removal units. The heat removal units utilized were a heat sink fin-fan and a double fan heat pipe (as illustrated in Figure 13 (a) and (b)). The study revealed no significant difference in the cooler

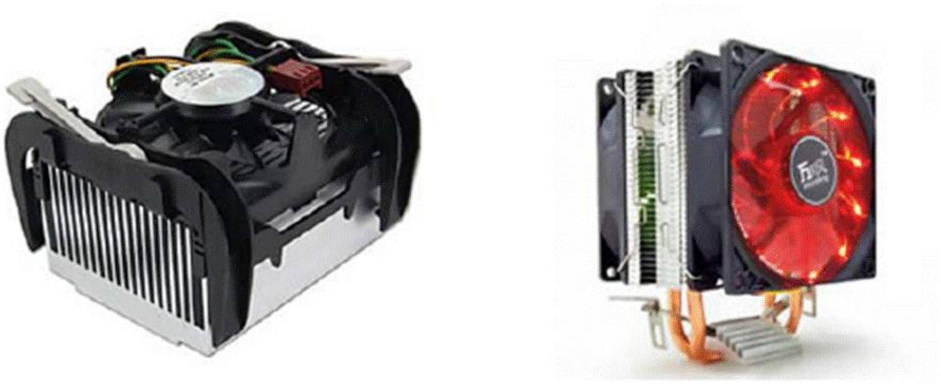


Fig. 13: Heat sink; (a) heat sink fin-fan; (b) double fan heat pipe [26].

box's performance when employing a double fan heat pipe or a heat sink fin-fan. The Carnot COP decreased over time, whereas the experimental COP initially increased with time, reaching a constant value after achieving a steady condition. Moreover, an increase in power resulted in a decrease in COP and an increase in temperature difference. In their experimental study, Ebong et al. [27] aimed to emphasize the significance of a cooling fan in conjunction with the Tec1-12706 thermoelectric module. The temperature variation on both the hot and cold sides of the module in the absence of cooling fans is represented (as illustrated in Figure 14). The graph highlights a drastic increase in the hot side temperature, reaching 400°C within 15 minutes, posing a potential risk of module damage. To address this, Figure 15 displays the temperature variation with cooling fans installed on both sides of the thermoelectric refrigerator. This configuration demonstrates more stable temperature levels, emphasizing the protective role of fans. The rapid rise in temperature on the hot side without a fan underscores the critical necessity of proper cooling. The study strongly advises against operating the system without a fan on the hot side. The accompanying graphs depict temperature readings obtained from the cooling chamber using a digital thermometer over 60 minutes, providing a comprehensive insight into the system's thermal dynamics. In their study, Kennedy et al. [28] explored the impact of air direction and flow rate within the heat sink on the performance of thermoelectric coolers. The researchers manipulated airflow in the cooling room using two distinct fan modes: blowing and sucking. Furthermore, they varied air velocity for both flow conditions. The findings revealed that employing the sucking mode of the fan at the lowest airflow speed resulted in the cooler attaining the lowest temperature compared to other combinations of fan modes and airflow speeds. These results emphasize the influence of fan mode and airflow velocity across the heat sink on the overall thermoelectric performance.

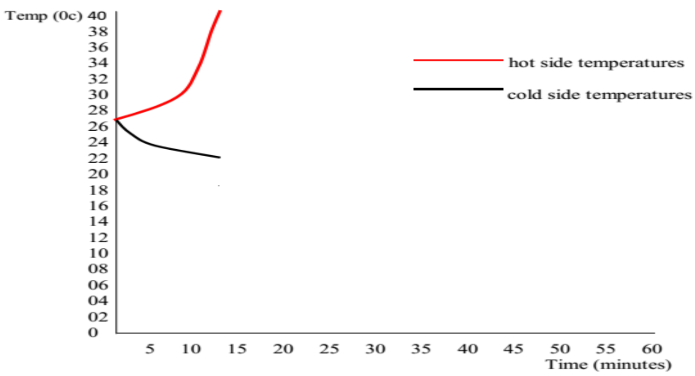


Fig. 14: Temperature changes on both sides of the thermoelectric refrigerator without a fan on the hot side [27].

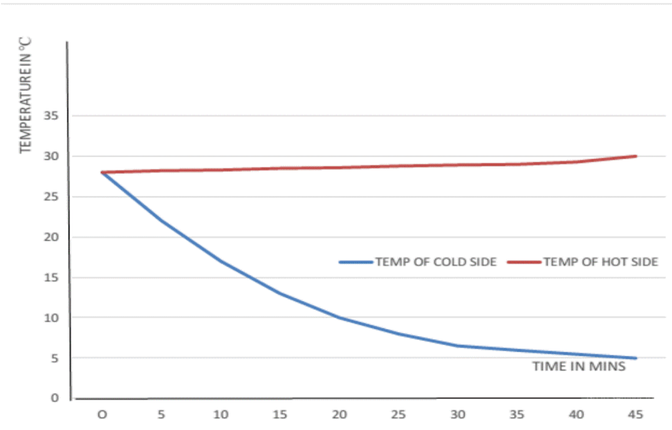


Fig. 15: Temperature changes on both sides of the thermoelectric refrigerator with fans. [27]

Pouryoussefi and Zhang's [29] research highlighted the substantial impact of free-stream air velocity on the thermal and hydrodynamic performance of the system. As the free stream velocity increases, there is a notable enhancement in the heat transfer coefficient.

In summary, the reviewed literature on thermoelectric coolers has made progress in optimizing heat sink designs like cross-fins and perforated pin fins, which improve heat transfer and reduce energy consumption. However, there remains a need for further studies to address existing gaps, particularly in understanding how fin shapes, airspeed, and electrical currents interact to affect cooling performance. Future research should focus on these interactions to develop more efficient and effective thermoelectric cooling systems, addressing current limitations and expanding their practical application.

3. Conclusions

Exploring various design parameters and optimization strategies has led to notable advancements in heat sink and thermoelectric cooler performance. Key findings include the positive impact of geometric modifications on heat transfer rates, such as perforations or alternative fin shapes. Fillet/chamfer additions and adjustments to fin thickness have demonstrated potential for enhancing heat transfer, contingent upon other influential factors. Here's the conclusion based on the key findings from the literature review:

- Introducing perforations or fins with different geometries (e.g., trapezoidal, triangular) can enhance heat transfer rates and the thermal performance of heat sinks. However, geometric factors like perforation size, shape, and arrangement influence performance.
- Introducing fillets/chamfers or modifying fin thickness can improve heat transfer, but their effects depend on other parameters.
- Dual-height fin profiles and cross-fin designs show potential for performance enhancement under natural convection.
- Heat sinks and fans are necessary to dissipate heat from thermoelectric modules and prevent overheating. Airflow direction and velocity significantly impact thermoelectric cooler performance. Both suction mode and higher airflow can lower attainable temperatures.
- Current/power selection is critical. Higher currents increase Joule heating and reduce efficiency, while lower currents limit cooling capacity. Optimal currents balance these factors.
- Two-stage designs with separate current pulse control on each stage can achieve lower temperatures and longer supercooling vs. single-stage designs.

- In thermoelectric coolers, there is a lack of research on the optimal design of heat sinks for enhanced heat dissipation, particularly in fin types and shapes.
- Additionally, strategies are required to minimize the power consumption of thermoelectric coolers. Furthermore, there is a need to optimize airflow around thermoelectric coolers and heat sinks to enhance cooling performance without significantly increasing power consumption.
- While some studies have investigated individual design factors, limited research examines the combined effects of these parameters on system performance. This gap hinders our ability to optimize thermoelectric cooler designs for maximum efficiency and effectiveness in real-world applications.

4. Research Gap and Future Recommendations

Identifying research gaps in thermoelectric coolers is crucial for guiding future research and development efforts. Here's a structured overview of the research gaps:

- Regarding Efficiency Improvement, the overall efficiency of thermoelectric coolers is relatively low compared to traditional cooling methods. Research is needed to discover new materials or configurations that can significantly increase the thermoelectric figure of merit.
- Considering Material Development, there is a continuous search for new thermoelectric materials that offer higher performance, are cost-effective, and are environmentally friendly.
- Regarding Durability and Reliability, Enhancing the durability of thermoelectric coolers under various operational conditions and extending their lives require further investigation.
- On the subject of Heat Sinks, research is needed to optimize the design of heat sinks for better heat dissipation, especially in compact spaces. In addition, identifying materials of the heat sinks that can improve the thermal conductivity of heat sinks while being lightweight and cost-effective and exploring the balance and integration of passive and active cooling methods to enhance the efficiency of thermoelectric cooling systems.
- Regarding input power, it is developing strategies to reduce the power consumption of thermoelectric coolers, making them more energy-efficient and suitable for battery-powered applications. In addition, advanced control algorithms can dynamically adjust the current input to optimize performance and efficiency based on real-time thermal loads.
- As for airspeed, research into the optimization of airflow around thermoelectric coolers and heat sinks to enhance cooling performance without significantly increasing power consumption is needed. Moreover, Addressing the noise generated by fans at high airspeeds is a concern in noise-sensitive applications.
- Numerous research studies frequently neglect the combined effect of the main parameters (heat sinks, current input, and airspeed) that affect thermoelectric coolers' performance.
- Addressing these research gaps requires a multidisciplinary approach, combining materials science, mechanical engineering, electrical engineering, and thermal sciences. Progress in these areas could significantly enhance thermoelectric coolers' performance, efficiency, and application scope.

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