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The Optimal Design of Heat Sinks: A Review

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Abstract. Heat sinks are used in industrial equipment to dissipate the excess heat from their heat-generating parts to the ambient. In the last few years, efforts on manufacturing electronic or mechanical devices with less weight, space, and lower cost were spent. Heat dissipation from the heat sink is stalling a big problem which many researchers are trying to solve. The aim of this study is to brief the previous investigation attempted enhancing the heat sinks thermal performance and to provide help to understand the cooling ability of their specific geometries. The various enhancement techniques used for optimizing the hydrothermal design of a pin fin, flat fin, micro-channel, and topology optimized heat sinks were summarized. The way in which the heat sinks' thermal performance is affected by orientation, shapes, perforation, slot, interruption, and space between fins and their arrangement under free and forced convection condition also reviewed.

Keywords: Heat sink, Optimal design, Pin and plate fin, Natural and forced convection.

1. Introduction

With the rapid development in electronic and mechanical devices (such as conditioning equipment, turbines, and electronic equipment), the need for efficient heat sinks with less size and weight has increased. The excess heat generated by these devices becomes a major problem which can cause damages in their parts. Furthermore, traditional cooling methods have become ineffective due to their limitations. The demand for developing effective ways to dissipate heat turns into a serious challenge. Therefore, researchers have been developing new effective techniques to solve the problem of high temperature. The heat transfer enhancement focuses on increasing the heat transfer rate between the hot surfaces with surrounding by raising the heat transfer coefficients or increasing the heat transfer area. Using extended surfaces (fins) is considered as a good technique which is widely used to enhance the heat transfer in various types of heat sinks [1, 2]. Different designs have been investigated in order to obtain optimized fin geometry. Interruption, slots, and perforation are examples of geometrical modifications that have been improved the thermal performance of fins or to reduce their weight or cost [3, 4]. A heat sink with working fluid which is called micro-channel heat sink is another technique in which the flow characteristics have an impact on the thermal performance. The fluid that fills the heat sink channels has a great influence on the heat removal rate [5, 6]. Various geometries have been utilized to increase the heat transfer rate in micro-channel heat sinks such as using circular, rectangular and trapezoidal cross-sections. Because the surface area of the microchannel is small, different modifications were used in order to maximize the heat transfer efficiency such as using rough surfaces, twisted tap and rib [7, 8, 9, 10]. Moreover, many researchers reported different shapes by using waves, zigzag and curves structures in which structures affect the flow characteristics in micro-channel heat sink [11, 12]. Another approach that introduces optimizing the geometry of a heat sink without predefining the shape or configuration of the final design is topology optimization [13, 14, 15]. Topology optimization can be defined as a mathematical science

approach which has been used in designing a heat sink due to its geometric freedom. In this approach, the computational domain is divided into a large number of elements. Each element has a relative density that determines whether the element is occupied by solid material or not. Therefore, the distribution of the relative density within the computational domain determines the heat sink geometries. In fact, there are many review articles that summarize the work previously performed by other researchers like [16, 17, 18, 19]. This paper mainly illustrates various designs of heat sinks and their geometrical parameters which have been designed by previous researchers during the last five years. It mainly focuses on the pins and flat surface fins heat sinks under free and forced convection due to their wide range of applications in industry and the modern design of microchannel heat sink. Besides, the effective topology optimization methods which are used in designing heat sinks.

2. Heat Sink Classification

A heat sink is a device, made of conductive metal, used to absorb heat from high-temperature parts and dissipate it to the surrounding. Heat sinks are commonly used in many industrial devices such as computer processors and air conditioning systems. Copper and aluminum are common metal used in manufacturing the heat sink. Most of the heat sinks designed with fins which are attached to the heat sink base to increase the heat dissipation area. There are two main techniques for heat transfer enhancement active and passive [20, 21]. Heat sinks vary in their shapes and applications, in this work heat sinks classified into four categories as follows:

2.1. Pin Fin Heat Sink

Due to their excellent heat transfer performance, pin fins have a wide range of applications in industries [22, 23]. Cylindrical, square, triangular and elliptical pin fins are examples of shapes used by many researchers to investigate their performance with the aim of increasing their efficiency [24 -28]. The previous works which used pin fins heat sink under free and forced convection along with the enhancement made with those pin fins are summarized below:

2.1.1. Optimal Pin Fin Heat Sink under Natural Convection

Mao-Yu and Cheng-Hsiung [29] examined experimentally and numerically the heat transfer rate for two different pin fin heat sinks under natural convection. The first was flat and solid heated base, while, the other had a hole in its heated base. The influence of the base plate, fin height, holes diameter in the base plate and the heat sink porosity on the heat transfer performance was also studied. The heat sink made of aluminum and the heated element was fitted into a copper block while attached to the heat sink. Figure 1 shows a schematic of a pin heat sink. The results showed that the heat transfer coefficient for hallow heated base heat sink is higher than that of the unhallow one due to greater acceleration and velocity in the circulation region. As the fin height, holes inside-outside diameter and input heat increases, the thermal performance increases. Finally, the hollow heat sink has a higher heat transfer coefficient than the solid heat sink when its porosity is ≤ 0.262 .

Sing [30], analyzed the thermal performance of a heat sink under natural convection by designing a model with ANSYS software. The ordinary circular pin fin with 32mm length was used then the diameter of the pin was modified by an angle of expansion of 1 degree, 2 degrees and 3 degrees outward as shown in Fig. 2. In this work, it was found that the 2 degree of expansion is the best modification as it dissipates more heat from the heat sink than other geometries.

Effendi et al. [31], predicted Nusselt number correction for a heat sink with round hollow hybrid fin (HHFHSS) under natural convection. CFD software has been used to generate a 3D-thermal model as shown in Fig. 3. 108 cases were studied, which include 36 arrangements with a different base temperature (50, 70 and 90°C). The numerical results have been experimentally validated. The developed Nusselt number correlation which is based on the fin height, Raleigh number, fin wall thickness, and external fin diameter, was shown to have reasonable accuracy with less than 20% difference compared to the complicated numerical correlation. Baldry et al [32] adapted a numerical 3D model by using COMSOL CFD program to design a heat sink that is used in thermoelectric cooling cap under natural convection. This study examined 19 configurations of pin fin heat sink with 6 different pin fin parameters which are number, diameter, height, wetted area, center to center spacing and arrangements. The results were experimentally validated with the traditional pin fin heat sink. This research developed a pin fin heat sink with base temperature equals 44.4 C and 10.9 kW-1 thermal resistance which meets the efficiency requirement for dissipation the waste heat from the cooling cap.

2.1.2. Optimal Pin Fin Heat Sink under Forced Convection

Al-Damook et al. [33], investigated experimentally and computationally the effect of perforation on the pin fin thermal performance and the pressure drops across a heat sink under forced convection with different flow rates. Two aluminum heat sinks were designed; the first with solid pin fin while the second with perforated pin fin (the same work done by [34]). The pin is 12 mm long with 2 mm diameter fitted with a regular array into a base plate with 6.5mm spacing between each two-pin centers. The perforated pins have holes with 1mm diameters with different locations as can be seen in Fig. 4. The results showed that the Nusselt number (Nu) for the perforation pin is 11% higher than that in the corresponding solid. As the perforation increases, the pressure drop increases to reach its maximum value when using 5 perforations. In contrast, the location of the perforation was shown to have a less enhancing influence on the thermal performance in the heat sink.

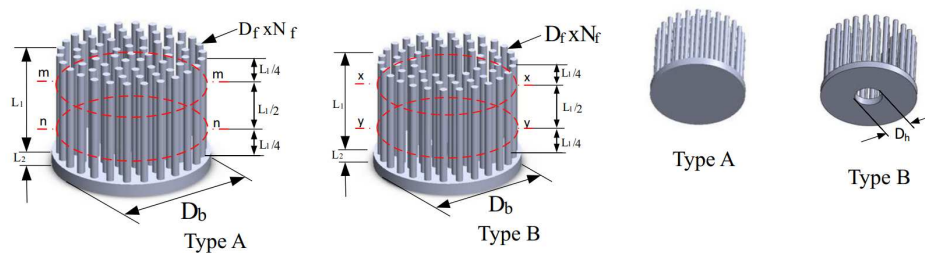


Fig. 1. Schematic of a pin fin configuration [29]

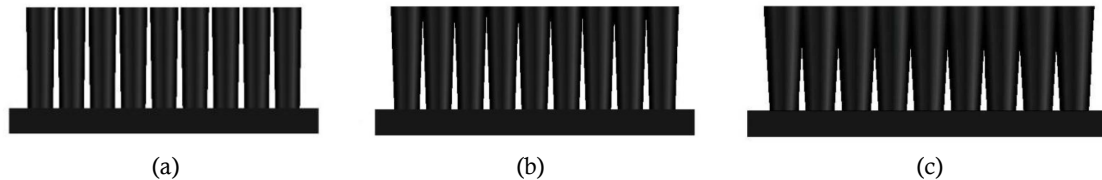


Fig. 2. The modified pin fin heat sinks with (a) 1 degree (b) 2 degree and (c) 3 degree of expansion [30]

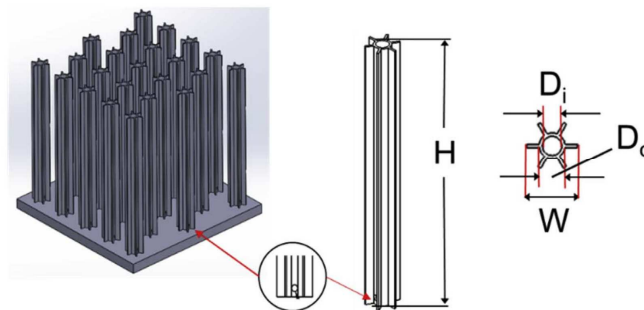


Fig. 3. The structure and design of the heat sink [31]

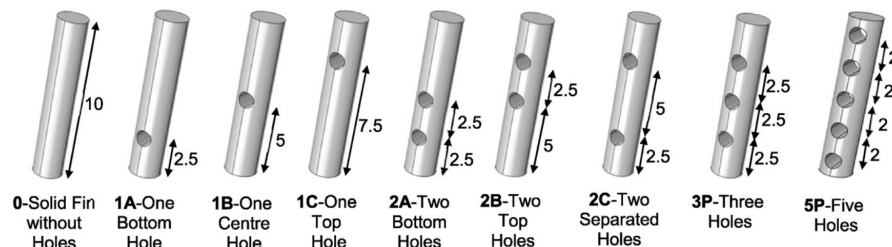


Fig. 4. The various numbers and locations of perforation in pin fin heat sink [33]

Mao-Yu and Cheng [35] conducted simulation studies by using COMSOL multiphysics software to examine the thermal performance under forced convection for the heat sink designed in their previous research [29]. Reynolds number (Re) range from 6468 to 45919 was studied and data obtained were compared with experimental data from other investigators. The results showed the highest heat transfer performance gained when a small hollow ($D_h/D_b < 0.15$) is used in the base plate heat sink. Maji et al. [36] studied numerically the heat transfer through a pin fin with different numbers, shapes, and sizes of perforation under forced convection by using inline and staggered arrangements. All the perforated fin heat performance and pressure drop were compared with the corresponding solid fin under the same conditions. ANSYS 14 fluent software was used to design the system models. Heat flux of 5903 W/m^2 was applied at the bottom of the base plate which has an area of $(0.1 \times 0.1) \text{ m}^2$ and a thickness of 3mm, where the fins are mounted either in inline or staggered. Figure 5 shows the different perforations geometries used and their numbers. The results showed that all perforated fins had higher thermal performance than the solid fins, especially with a staggered arrangement. The Nu number increases and the pressure drop decreases as the perforation number and size increase. The maximum heat transfer rate obtained by using elliptical fins with elliptical perforation is higher by 40.5 % than that of the solid circular fin.

Maiti and Prasad [37], carried out a computational study on the heat transfer performance and the pressure drop in a fin heat sink under forced convection. Solid cylinder, slotted cylindrical, and kidney fin geometries were designed as shown in Fig. 6. Reynolds number ranged from 2000 to 11000. The results obtained were validated with experimental results from previous work, and they found that the higher heat transfer rate acquired by using slotted kidney fin shapes with a staggered arrangement. Moreover, the decrease in pressure drop associated with the slotted fin was higher than that associated with the solid fin for both geometries, cylindrical and kidney.

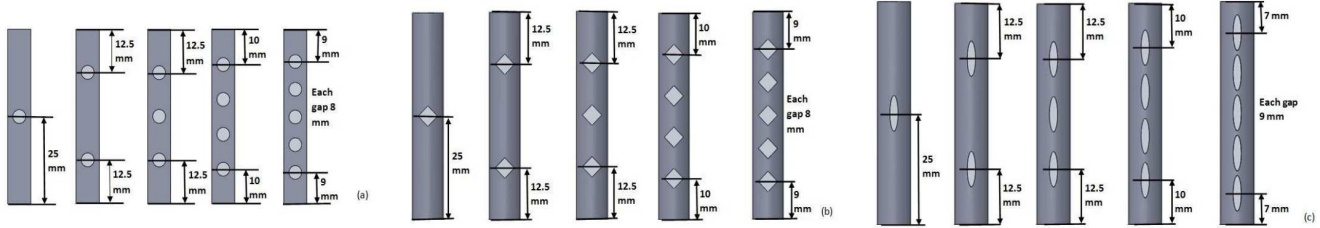


Fig. 5. Fins with circular, diamond and elliptical perforation shapes [36]

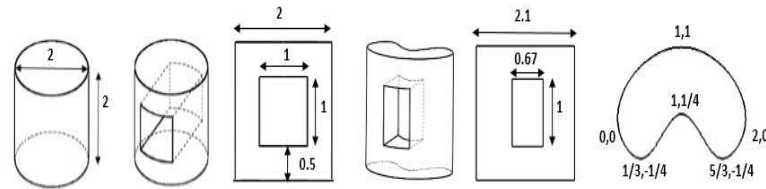


Fig. 6. Geometries and dimensions of the different fins [37]

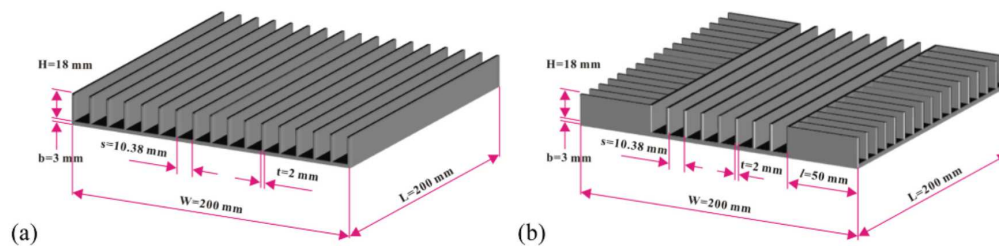


Fig. 7. Design and dimensions of (a) plate-fin heat sink and (b) cross-fin heat sink [49]

Khonsue [38], conducted an experimental study to calculate the heat transfer rate and pressure drop of mini pin-fin heat sink under forced convection to make a guide for the design and development of electronic devices. They used 63 aluminum pin fins with three different configurations, Rectangular, cylindrical and spiral pin-fin configurations. The experiments were carried out under a constant heat flux ranging from 9.132 to 13.698 kW/m² and the air Reynolds number range was from 322 to 1982. The results showed that the spiral pin fins had the highest heat transfer coefficient and Nusselt number compared to the other configurations. On the other hand, the minimum pressure drop was obtained when the rectangle pin fin was used. Tijani and Jaffri [39], investigated numerically and experimentally the influence of circular configuration on thermal performance, pressure drop and temperature distribution of two finned heat sink geometries under forced convection. The experiments were performed with a constant heat flux of 50 W. The heat sink was placed inside a channel where air flowed through with a velocity range from 1 m/s to 3 m/s. solid and perforated pin fin and flat plate were designed together and compared in this work. The results showed that perforated pin and flat fin enhanced the heat transfer coefficient by 8.3% and 6.3% more than the corresponding solid fins respectively. Also, the Nusselt number was increased by 2% to 4% when perforated pin fin was used instead of a solid pin fin. The perforated fin had a smaller pressure drop in the experiment.

2.2. Flat Fin Heat Sink

The flat fin is one of the popular augmentation design used in a heat sink. Many researchers enhanced flat fin heat transfer performance by making holes, interrupted and rough surface, etc. [40]. The following are some of the enhancements made to flat fin in previous work.

2.2.1. Optimal Flat Fin Heat Sink under Natural Convection

Awasarmol and Pise [41], carried out an experimental study to investigate the thermal performance of a perforated fin in a heat sink with different holes diameters and angles of inclination under natural convection. The perforations diameters ranged from 4 to 12 mm, the input powers supplied ranged from 15 to 35 W, and the angles of inclination ranged from 0° to 90°. The effect of these parameters was studied and the results are compared with the corresponding solid fins under the same conditions. The results obtained showed that the fins with 12 mm perforation diameter and 45° angle of inclination had a higher heat transfer coefficient with 32% enhancement over the solid fin. Also, perforation fins saved about 30% in the material by mass. Shitole and Arkirimath [42], presented an experimental work to calculate the heat transfer rate of a heat sink by using a vertical perforated plate under natural convection. Aluminum fins with dimensions of (200 × 200 × 20) mm and with different shapes (circular, square and triangular) and perforation size were used and compared with the non-perforated fin. The area of perforation was varied from (33.2 to 176.8 mm²) and the heat input was varied from (60 to 120 W) to investigate their influence on the heat transfer coefficient. The results showed that the heat transfer increases by increasing the heat input supply as well as perforation area. Moreover, the circular perforation had a higher heat transfer coefficient than the triangular perforation. Prasad et al. [43], carried out an

experimental study to investigate the effect of a number of perforation on the heat transfer rate for a cylindrical heat sink under natural convection (the same work done by [44, 45]). The voltage supplied to the heat sink was ranged from 100 to 220 V. The perforation diameter was constant but their number ranged from 24 to 60. The experimental results were compared with results obtained from computational analysis using the ANSYS program. The results showed that the heat dissipation increases by 20% to 70% as the perforation number increases from 24 to 60. Venkitaraj and Sanooj [46], investigated numerically the heat transfer enhancement by using fins with different perforation shapes under natural convection. Circular, square, elliptical and triangular perforations with a variety of diameters are designed. The heat input supplied to the heat sink ranged from 15 to 30 watt. The results obtained were compared with that obtained when using solid fin under the same conditions. It was found that the perforation fin dissipates more heat than solid fin [47] and the maximum heat transfer coefficient ($9 \text{ W/m}^2\cdot\text{K}$) was achieved by using perforation area equivalent to 12 mm diameter. In addition, circular and elliptical perforation shapes nearly have the same characteristics [48]. Triangular perforation had the lowest heat transfer coefficient among the other shapes. Feng et al. [49], investigated experimentally and numerically the heat transfer enhancement by using cross fins heat sink under natural convection. The thermal efficiency of the cross fin heat sink was compared with the corresponding plate fin heat sink in a horizontal orientation. The plate fin heat sink dimensions were 200mm length, 21mm height, and 2mm thickness. The cross fin heat sink has the same dimensions, but the length of the short fin was 50 mm as shown in Fig.7. The heat supplied ranged from 20 to 60 watt. The results showed that cross fin heat sink enhanced the heat transfer coefficient by 15% with the same volume and materials used in reference plate fin and without more cost.

Hussein [50], performed an experimental study to investigate the effect of v-corrugated perforation and non-perforation fin on the thermal performance of a heat sink under natural convection. The heat input to the heat sink was varied by varying the voltage supplied from 110 to 200 V. the fins were made from aluminum with 250 mm length, 250 mm width and, 2 mm thickness. The first fin is v-corrugated solid while the second fin is v-corrugated with inline arrangement circular perforation; the third fin is v-corrugated with staggered arrangement circular perforation. The results obtained were validated with empirical results from previous literature [51]. The heat transfer coefficient and the heat dissipation for V-corrugated solid fin are greater than the flat [52, 53]. The heat transfer coefficient for a v-corrugated perforated fin was improved by 20% and 27% more than the corresponding solid for the inline and staggered arrangement respectively. Also, the results showed that perforation fin with staggered arrangement dissipated more heat than the inline arrangement by 22%.

Mousavi et al. [54], estimated numerically the heat transfer performance for 10 various configurations vertical finned heat sink under natural convection. 3D simulation by CFD software fluent 6.3 was made and compared with the previous experimental and theoretical investigation [55]. The vertical finned heat sink is of 305 mm length and 101 mm width. The fine configurations used in that work was shown in Fig.8. The results showed that decreasing the space between interrupted fins did not improve the cooling process. The capped fins enhanced the heat transfer rate but they have a higher weight than a continuous fin. In contrast, L-shape and cut-capped fins have less weight with higher heat transfer performance than other fins. Haghighi et al. [56], conducted an experimental investigation to study the thermal performance of a plate-cubic pin fin heat sink under natural convection. Six fins were designed with different configurations; fin numbers and fins spacing. The heat supplied was varied from 10 W to 120 W. The results showed that the plate cubic pin fin enhanced the heat transfer by 10 - 41.6 % and have lower thermal resistance compared to the normal plate fin. Also, the thermal performance improved as the fins spaces and fin numbers increased. The results of that work demonstrated that the optimal design was by using plate-cubic pin fin heat sink with 7 fins and 8.5mm spacing.

2.2.2. Optimal Flat Fin Heat Sink under Force Convection

Shadlaghani et al. [57], studied numerically the optimal fin designed to get a higher heat transfer rate for a heat sink under forced convection. First, triangular, rectangular and trapezoidal fins with constant volume were examined as shown in Fig. 9. They found that the triangular shape had a greater heat transfer rate than other shapes. Second, the cross-section of the triangular fin was investigated and the results showed that when the ratio of fin height to its thickness increases, the heat transfer rate increases. Third, the convection enhanced by using longitudinal different shape perforation with different locations as can be seen in Fig. 10. Results also showed that rectangular perforation with 0.3 (H_c/H) location is the optimal design which gave the higher heat transfer rate.

Singh et al [58], analyzed computationally the heat transfer coefficient, Reynolds number (Re) and Nusselt number (Nu) for perforated fin heat sink under forced convection. CFD program was used to design the fins with circular, rectangular and slotted perforation with the same surface area. Reynolds number was varied from 8000 to 35000 with a constant heat input of 100 W. The results showed that fin with circular perforation dissipated more heat than the other configurations. Besides, other perforation shapes were also shown to have a high heat transfer coefficient and Nusselt number [59]. Anish and Kanimozhi [60] determined experimentally the heat transfer coefficient of rectangular fins with the circular notch, triangular notch and without notch under forced convection. The test section was made of aluminum plates with $190 \times 110 \times 1$ mm dimensions. These plates were modified by making a circular and triangular notch at their centers with 20 % notch area as can be seen in Fig. 11. Experiments were carried under different heat flux values that ranged from 200 to 360 W and with various airflow rates. The results indicated that fins with circular notch have a heat transfer coefficient range from 10.34 to 10.55 $\text{W/m}^2 \cdot ^\circ\text{C}$, compared to 10.08 to 10.29 for triangular notch and 9.6 to 9.76 for fin without a notch.

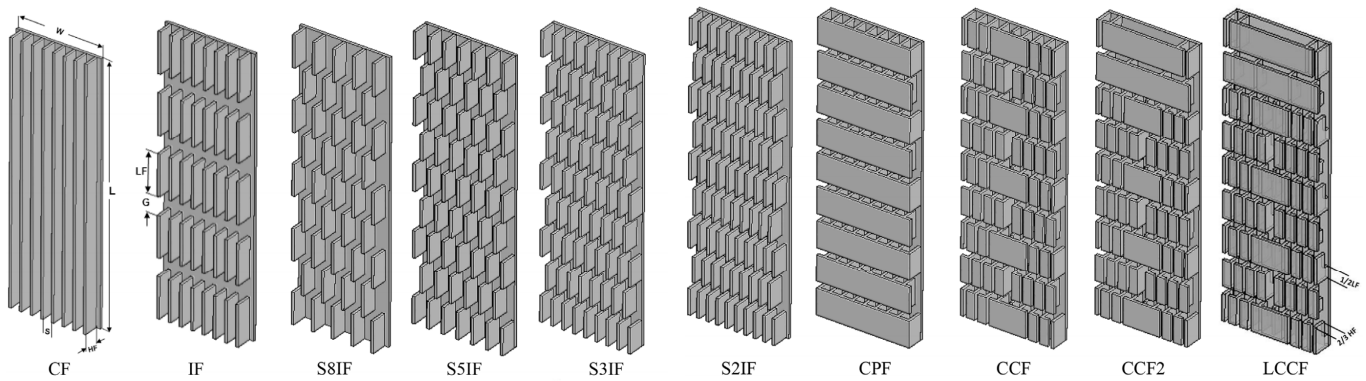


Fig. 8. Schematics configurations of the heat sinks [54]

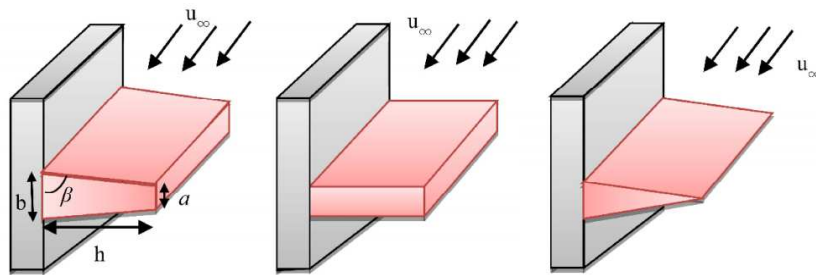


Fig. 9. Fins with different geometries: (a) trapezoidal, (b) rectangular and (c) triangular [57]

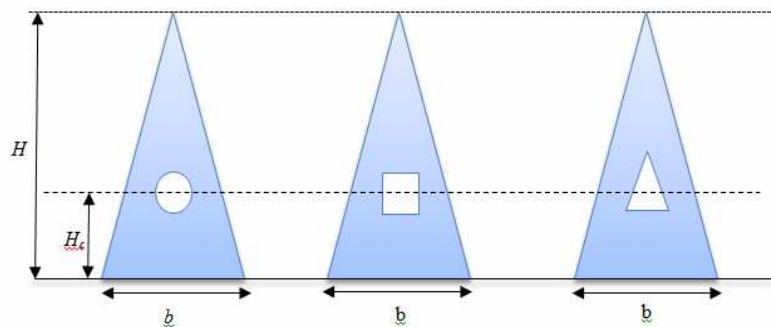


Fig. 10. Triangular fin with different perforations shapes [57]

Salam et al. [61], carried out an experimental analysis to compare the performance of solid fins and perforation fins under forced convection. Three aluminum fins with a 10 cm length, 5 cm width, and a 3 cm thickness were used. The first fin was solid; the second was drilled along the lateral axis of the fin with 6mm diameter of circular perforation, and the third with 9mm diameter of circular perforation. The results showed that the perforated fin had a higher Nusselt number (Nu) with a lower pressure drop and more weight reduction than the solid fin. Yadav et al. [62], modeled numerically a fin heat sink with different holes configurations to study their effects on heat transfer rate under force convection by using the COMSOL program. The heat sink was (13 × 13 × 1) mm dimensions and the fin was a 20 mm length, 15 mm width, and a 12 mm height. Circular and rectangular perforations were used with the same surface area of 25.13 mm² and this was achieved by changing the size and number of perforation. The results showed that the perforation fins dissipate 3.5 – 5.5 % more heat than the solid fin with 34 – 40 % reduction in the wetted area. Al-Sallami et al. [63], studied numerically the optimal design of a finned heat sink under forced convection. They explored and compared the effect of longitudinal circular, notch and slot perforation on the heat transfer rate and pressure drop with corresponding solid fin. Aluminum heat sink with base plate dimensions (50 × 50) mm and a 2 mm thickness was used. The fin height and thickness were the same in all cases and equal 10mm and 2mm, respectively. The first fin geometry was solid while the second fin was with 1, 2, 3 and 4 circular perforations with 1mm diameter. The third geometry was three fins with rectangular notches with 1mm width and different heights (2.5, 5 and 7.5 mm). The last geometry was three slotted fins with slot width equal 1mm and different heights (3, 6 and 10 mm) as shown in Fig.12. The result showed that the fins with notch perforation exhibit a significant advantage compared to the other perforations in terms of heat transfer and pressure drop. The notch perforation fin reduced the temperature of the heat sink base below its critical temperature with less fan power and less material.

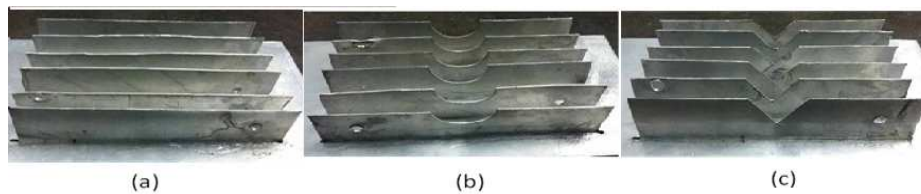


Fig. 11. Plat fin (a) without notch (b) with circular notch (c) with triangular notch [60]

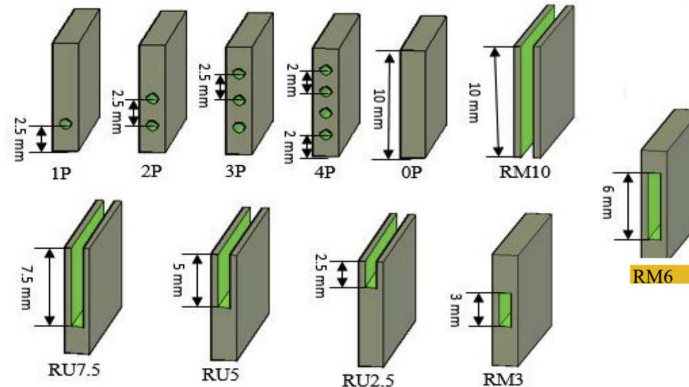


Fig. 12. Designs and dimensions of the fins [63]

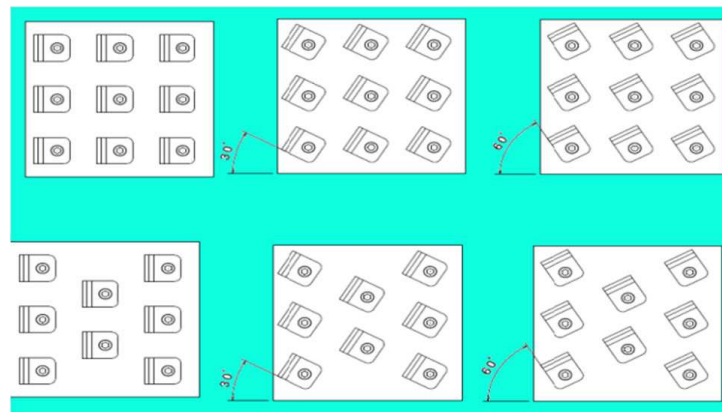


Fig. 13. Different fin orientation for vertical plates fin heat sink [65]

Ibrahim et al. [64], investigated experimentally and numerically the heat transfer performance of a heat sink by using perforated and non-perforated fins under forced convection. The heat sink was an aluminum plate with a 195 mm length, 120 mm width, and 15 mm thickness. Four fin geometries were chosen in this experiment; all of them were (120 × 85) mm dimensions. One of them was solid while the other was perforating with circular, rectangular and triangular perforation. The air velocity used was varying from 1.8 to 2.8 m/s with 0.2 steps. The results showed that the perforated fins have a heat transfer coefficients 35.8% to 51.29% higher than that of the solid fin according to perforation shapes. Paitil and Dingare [65], investigated experimentally and numerically the heat transfer performance of a rectangular plate fin heat sink at varying orientation and arrangement under force convection. Three fins inclinations 0°, 30° and 60° degree with inline and staggered arrangement were studied as shown in Fig.13. The experiments were carried out with Reynolds number ranged from 4000 to 18,000 and different heat supplies (50, 80, 100 and 125 W). The results showed that the maximum heat transfer coefficient was obtained at 30° inclination with inline arrangement whereas at 0° for the staggered arrangement. The heat transfer associated with the 0° inclination with the staggered arrangement was 17 % higher than that associated with the 30° inclination with the inline arrangement and 76 % higher than that for flat plate fin.

Gupta et al. [66], investigated experimentally the heat transfer performance of a heat sink by using dimples and protrusions plate fin under forced convection condition. The plate fin was made of aluminum with 180 mm width and 80 mm height. The effect of dimples depth and pitch for inline and staggered arrangement on the Nusselt number and friction factor was also indicated. The experiments were carried out under Reynolds number range from 6800 – 15200 while the heat flux and dimples diameter was constant. Results showed that using the heat sink with dimples fins enhances the heat transfer, friction, and the fin performance compared to that of a smooth fin. The heat transfer rate and flow performance increase by developing the depth of the dimples. The maximum Nusselt number was obtained by using dimples fin with the staggered arrangement with dimple pitch and depth ratio of 2.5 and 0.5 respectively. Bouchenafa et al [67] investigated numerically the effect of wavy plate fins on the heat sink performance under forced convection. The influence of the wave amplitude and numbers of waves on the Nusselt number and pressure drop was

also analyzed are compared with the flat fin heat sink. By comparing the two heat sink configurations, higher heat transfer rate and pressure drop obtained from the wavy fin heat sink. Moreover, the wavy plate with a higher number of waves and amplitude had a lower thermal resistance. Hoi et al. [68] optimized numerically the design of flat plate heat sink with fractal grid-induced turbulence under force convection by using CFD ANSYS fluent program. The grid fin separation, fractal thickness ratio, and inter fin distance were studied numerically at Reynolds number equal 2×10^4 . The results obtained were validated with previous work by [69, 70] and showed that maximum Nusselt number was 3661 which was obtained by using 9.77, 0.005 mm and 0.01 mm for thickness ratio, inter fin distance and grid fin distance respectively. This value of Nusselt number was increased by 6.1% as compared to the reference case, and by 16.3% for the other configuration used in this study. Hussain et al. [71] investigated numerically the effect of fillet profile and flow direction on the heat sink thermal performance under forced convection. Two heat sink configurations were designed, the first one was with fillet profile and subjected to parallel flow, while the other one was without a fillet and subjected to impinging flow as can be seen in Fig. 14. The radius of the fillet fin is 1.5 mm and the heat sink base dimensions were the same in both cases ($40 \times 39.7 \times 1.5$ mm). The results showed that the heat sink with fillet fin profile had base temperature and thermal resistance that are 7.5% and 18% respectively lower than the non-fillet one.

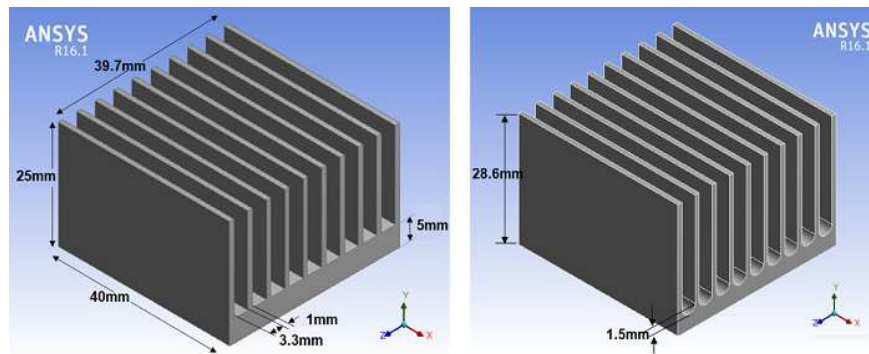


Fig. 14. The geometrical model (a) non-fillet profile (b) fillet profile [71]

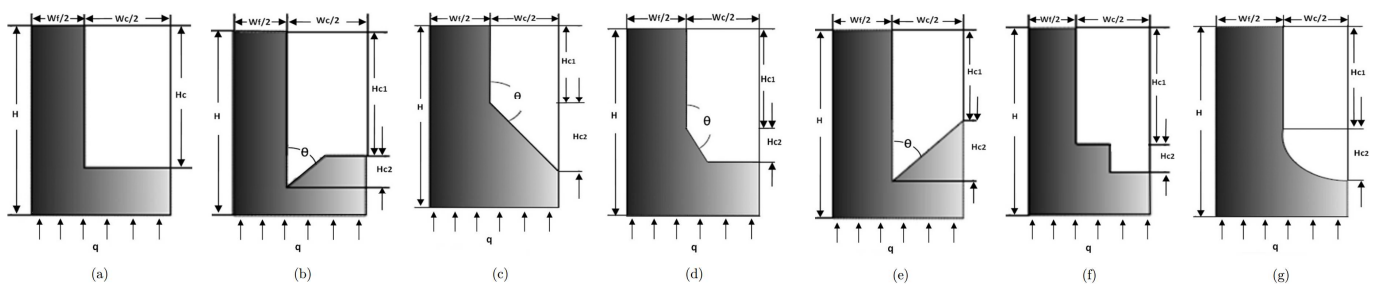


Fig. 15. Various Geometrical cross-sections for micro-channel heat sink. (a) Rectangular, (b) inverse trapezoidal, (c) triangular bottom, (d) trapezoidal bottom, (e) W shape, (f) varied width rectangular, and (g) semi-oval [77]

Taimoor et al. [72] examined experimentally the thermal performance of a heat sink with hexagonal perforated fin under forced convection. The Nusselt number, heat transfer coefficient, thermal resistance, fin efficiency and fin effectiveness for a perforated fin were calculated and compared with the non-perforated fin. The results demonstrated that Nusselt number, heat transfer coefficient fin efficiency and fin effectiveness for a perforated fin are greater than those for non-perforated fin. Meanwhile, the thermal resistance and pressure drop for a perforated fin are smaller than solid one under the same conditions.

2.3. Micro-channel Heat Sink

Microfluidic devices are being widely used in different heat transfer applications and, thermal performance in micro-channels become a serious challenging issue. As a solution, different geometries of micro-channel heat sinks have been employed to enhance the heat transfer. Khan et al. [73] analyzed numerically the effect of ribbed channels on the performance of a micro-channel heat sink by using three dimensional Navier-Stokes analysis. Six rib shapes were used in laminar flow with Reynolds number ranged from 100 to 500. The ribs dimensions were fixed and the results obtained with the traditional channel. From the results, it was found that using ribs in micro-channel improves the heat transfer rate and reduces the thermal resistance. Also, the Nusselt number and pressure drop in ribbed channel increased gradually as Reynolds number increased. Those results also proved by other researchers [74, 75]. Among the various configurations of the ribs, the triangular rib showed the smallest thermal resistance while the rectangular rib resulted in the highest pressure drop. Xia et al. [76] studied experimentally and analytically the heat transfer performance and fluid flow characteristics in a micro-channel heat sink with complex corrugation channels. The thermal resistance and amount of enhancement were determined and compared with the smooth rectangular channel. The dimensions of the two channels were the same and the max/min widths of corrugation were 0.2/0.1 mm with 0.2 mm pitch. The results indicated that thermal performance for the corrugated channel was enhanced by 1.24 for Reynolds number equal 611

and the thermal resistance was reduced by 18.99% than the regular rectangular channel. Khan and Kim [77] investigated numerically the thermal and hydraulic performance of various configuration micro-channel heat sinks by using the ANSYS CFD program. The design of the seven geometries used in this research can be seen in Fig. 15. Nusselt number, friction factor, and thermal resistance were studied with a Reynolds number ranged from 50 to 500. The results showed that the inverse trapezoidal configuration introduced the best thermal performance and highest Nusselt number with the lowest increasing rate in the thermal resistance. Those results were also proved by [78] who investigated the thermal performance and resistance of micro-channel heat sink with three different configurations of the channel cross-section area (Trapezoidal, square and semi-circular). The design with trapezoidal cross-section provided the least thermal resistance

Osanloo et al. [79] evaluated numerically the thermal, bottom wall temperature and pressure drop of a double layer microchannel heat sink with tapered lower and upper channel. Different flow rates of coolant fluid and convergence angles were studied. The results showed that the pressure drop and thermal resistance were significantly increased and the temperature of the bottom wall was reduced by increasing the volumetric flow rate and the convergence angle from 0° to 6° , in this cases the pumping power also increased [80]. The research showed that the optimal convergence angle was 4° which introduces the best temperature distribution with less thermal resistance. Ansari et al. [81] analyzed numerically the effect of randomly hotspots on the performance of a double layer microchannel heat sink by using 3D Navier Stock equations. Two double-layer microchannel heat sink was designed with the same dimensions. The first one with parallel channels and the other with cross channels design, as shown in Fig. 16. Eleven hotspots were introduced with three different schemes. These hotspots distributed randomly depending on the design of the experimental techniques. The numerical analysis carried out with Reynolds number ranging from 400 to 933. The model was validated with experimental results from kinds of literature [82, 83]. From the results of that work, it can be concluded that the heat sink with the transverse flow and multiple hotspots is considered the best choice for cooling due to its lowest temperature variation and thermal resistance among the other schemes.

Jing and He [84] studied numerically the thermal performance of a staggering double-layer microchannel heat sink (DLMCHS). The influence of inlet velocity, geometrical parameters such as the offset between the lower and upper layer of micro-channels and vertical rib thickness on thermal resistance also investigated. The results showed that the geometrical parameters highly affected the thermal performance of the DLMCHS. This statement completely agrees with [85] who showed that hydraulic resistance and heat transfer of fluid flow in a micro-channel is strongly dependent on the geometric parameters of the channel. Deng et.al [86] studied numerically the hydraulic and thermal performance of double-layer microchannel heat sink (DL-MCHS) with various cross-sectional geometries. Five DL-MCHS were designed with triangular, trapezoidal, rectangular, circular and reentrant as can be seen in Fig. 17. The thermal resistance, pressure drop, and wall temperature distribution were compared for all these configurations and the single layer (MCHS). The results showed that DL-MCHS decreases the wall temperature with a 27% reduction in thermal resistance. Among the five geometries of DL-MCHS, the rectangular shape was shown to be the best choice for the best thermal performance, whereas the reentrant shape required the least pumping power. While, the trapezoidal shape showed the worst pressure drop, thermal resistance, and pumping power.

2.4. Topology Optimized Heat Sink

Topology optimization is a new method used by some researchers for thermal optimization of heat sink configurations without specifying a fin shape. Dede et al. [87] presented a topology optimization method for steady-state conduction with side convection to design a 3D air-cooled heat sink. In this research, the additive layer manufacturing (ALM) approach was used to fabricate the optimized heat sink. The benefit of using the ALM approach is to design complex geometries or external profiles that cannot be designed by using the conventional manufacturing method. The thermal resistance and pressure drop for optimized heat sink versus different airflow rates were studied (numerically and experimentally) and compared with heat sink designs that have straight plat, radial plate, stepped straight plate and staggered pin fin arrangement which is fabricated by using conventional machining techniques in kinds of literature. The results showed that the optimized heat sink had lower thermal resistance and pressure drop than the other heat sink geometries. Alexandersen et al. [88] applied the density-based topology optimization method to design a 3D heat sink cooled by natural convection by using a fully coupled non-linear thermofluidic model. Various optimized designs are implemented in laminar flow conditions with Grashof number ranged from 103 to 106. The methodology used in this work is capable of avoiding problems with the formation of non-physical internal cavities, recovers interesting physical effects and insights and length-scale effects and artificial convection assumptions. The results were verified with the results obtained from the finite element analysis method performed by the COMSOL program and showed good agreement. The results showed that the branches of the designed heat sink increase as the Grashof number increase. In addition, the complex geometries can notably enhance the cooling behavior compared to the simple fin geometry. Joo et al. [89] optimized the thermal performance of a heat sink in natural convection by using topology optimization method. In order to predict the shape-dependent influence of the heat sink, a surrogate model that is applicable to arbitrarily shape structures was used with the effective channel spacing. The thermal performance of the optimized heat sink was compared to that of a plate-fin heat sink from the numerical correlations. To determine the thermal performance of the optimized heat sink, the finite volume method was used and implemented in the ANSYS software program. The four-volume fractions used in this work can be seen in Fig. 18. The results obtained showed that the thermal resistance of the optimized heat sink is 15% lower than that of the conventional heat sink with 26% material saving.

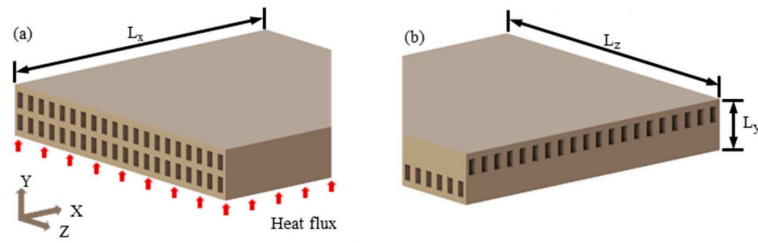


Fig. 16. Schematic diagrams: (a) parallel-channel design; (b) cross-channel design [81]

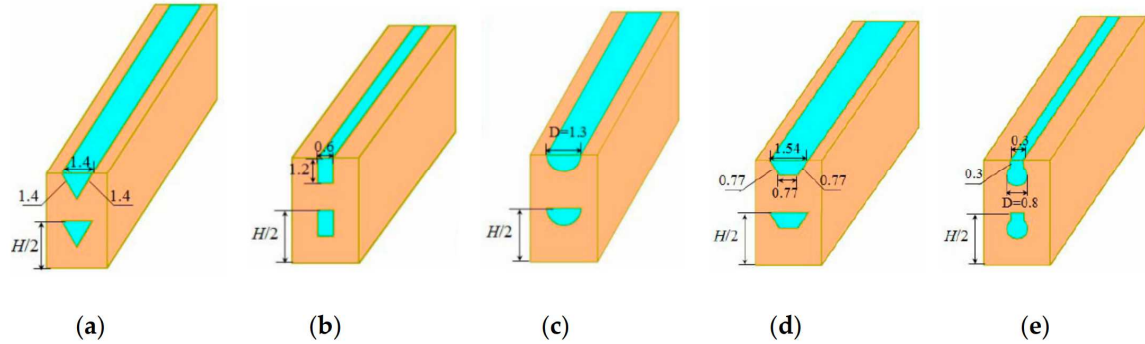


Fig. 17. Schematic of the DL-MCHS with different micro-channel cross-sectional shapes: (a) triangular; (b) rectangular; (c) circular; (d) trapezoidal; (e) reentrant shaped [86]

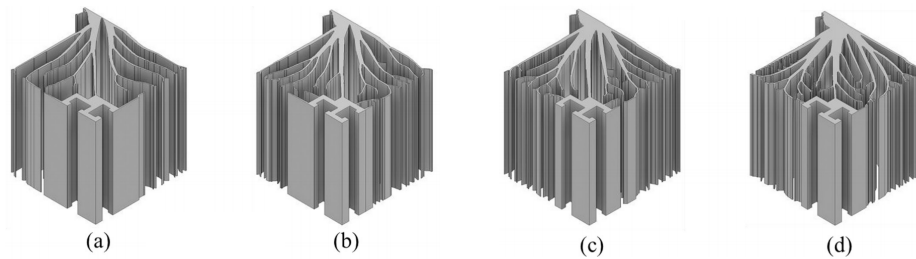


Fig. 18. 3D topology optimized heat sink with volume fraction (a) 0.19 (b) 0.23 (c) 0.27 (d) 0.31 [89]

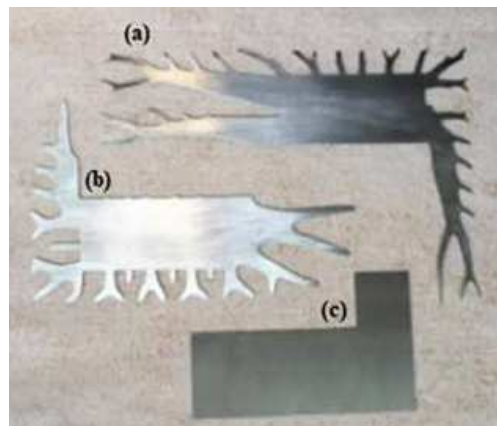


Fig. 19. The aluminum heat sink plat (a) non-robust (b) robust (c) L-shape [90]

Maradiaga et al. [90] designed and modeled a topology optimized heat sink to enhance the thermal management of the tablet by using the COMSOL optimization module. Three aluminum heat sinks were designed, the first one as L-shape heat sink and the others were topology optimized by using the robust and non-robust approach as can be seen in Fig.19. The robust approach provides sharper edges to the optimized heat sink. These sharp edges have no zones with intermediate densities. Therefore, they are easy to manufacture. The results showed that the non-robust heat sink has the lowest average temperature and the highest heat transfer coefficient in experimental and numerical modeling. Zeng and Lee [91] designed a 3D liquid-cooled micro-channel heat sink (MCHS) by using the topology optimization method. The model was implemented depending on the derived accurate 2D model with considering minimum pressure drop and average temperature. The optimized MCHS was performed for different velocities on the conventional straight channels. The results indicated that the optimized MCHS saves about 50% of pumping power with high thermal performance.

3. Conclusions

The optimal design of a heat sink aims to enhance the heat removal process with less mass, size, frictional losses, cost and weight with better performance. In the present paper, the techniques implemented in previous researches to increase the thermal efficiency of heat sinks for the last 5 years are reviewed. For plate and pin fin heat sink, the shapes, orientation, perforation, slot interrupted fins dimensions; space between fins and their arrangement under free and forced convection conditions are examined. The Micro-channel heat sinks with different sizings, geometries, and cross-sections, using turbulators, single- and double-layers, and topology optimized heat sinks are also reviewed. The following conclusions can be drawn:

1. For forced convection, as the Reynolds number increases the Nusselt number, heat transfer rates and pressure drop also increases. Fins with perforation, slot, corrugated, dimples, notch, and interruption for either free or forced conditions showed a better heat transfer rate than the solid fins. Staggered arrangement for a pin fin, flat fin, perforations, and slots showed good enhancement in heat transfer coefficient compared to the inline arrangement. The spacing between fins had a significant influence on the heat sink performance. As the space increases, the heat performance increases. The amount of heat removal from the heat sink is largely affected by the orientation and inclination angle of the fins. Two basic considerations are used in optimizing the heat transfer performance, the amount of heat removal and the heat removal per unit weight. When the total heat dissipation is the basic demand, the optimal plate-fin heat sink is more efficient than the optimal pin fin heat sink. In contrast, the optimal pin fin heat sink dissipates more heat per unit weight than the optimal plate-fin heat sink in many practical applications.
2. The thermal performance of a micro-channel heat is significantly enhanced by using a double layer, different channel geometry, turbulators and ribs between channels. Nevertheless, using augmentations can result in a high-pressure drop in some applications and need more pumping power than a smooth single layer microchannel heat sink.
3. Topology optimization is a powerful method for designing heat sinks capable of maintaining a low operating temperature in limited space. The topology optimization designing approach leads to branching, tree-shaped flow network designs. This type of fins shapes create more complex flow phenomena in force convection conditions like secondary flow, boundary initiation, flow mixing and participating in the enhancement of thermal and hydraulic performance. However, more experimental validation is needed to improve and confirm the topology optimization method.

Author Contributions

H.T. Dhaiban planned the scheme, collected the previous literatures and suggested the review classifications. M.A. Hussein initiated and wrote the research; all authors discussed the conclusions, reviewed and approved the final version of the manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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