Hydrothermal Performance Enhancement in Different Types of Perforated Heat Sinks: a Review

Amer Al-Damook[1,2,] Waleed Al-Sallami[3], Mushtaq T. Al-Asadi [3,4], Nabeel Abed[5], Wissam H. Khalil[1,2]
eng.ajsh2006@uoanbar.edu.iq, ml13wtia@leeds.ac.uk, mushtq55@yahoo.com, nabilkhalil90@gmail.com, wissam.gmw@uoanbar.edu.iq
[1]Mechanical Engineering Department, University of Anbar, Iraq
[2]The Renewable Energy Research Centre, University of Anbar, Iraq
[3]School of Mechanical Engineering, University of Leeds, UK
[4]Refrigeration Department, Eng. Division, Basra Oil Company, Ministry of Oil, Basra, Iraq
[5]Mechanical Technical Department, Technical Institute of Anbar, Middle Technical University, Iraq

***Abstract*— The revolution developments in electronics motivate researchers to enhance the heat transfer by providing efficient systems in limited space. An effective way to enhance the heat transfer is geometry modification which is the focus of this review article. One of the famous geometries to improve the heat transfer is perforated micro-channel heat sinks (PMCHS). Thus, the findings of related published articles are presented intensively in terms of heat transfer, fluid flow, methods, power consumption and energy management.**

Keywords— Perforated Pinned HSs, Perforated Finned HSs, Hydrothermal Enhancement for Applications, Liquid and Air Cooling Techniques, Laminar and Turbulent flow.

I. Introduction

Education, business, transportation, social media and the economic sectors have become very dependent on Information and Communication Technology (ICT), to which end, ICT has become the most important source of information and data in our society (Zeadally et al., 2012). Thus, data centres, which are essentially digital factories, have become a vital part of ICT processing, management, storage and exchange of data and information (Pan et al., 2008). A data centre consists of four main parts: power equipment such as power distribution units and batteries, cooling equipment (chillers and computer room air-conditioning (CRAC) units), IT equipment (servers, storage and network), and miscellaneous component loads (lighting and fire protection systems) (Dai et al., 2014). Electronic component systems that arrange processing, storing and transmission of data is the main part of the data centre, according to Shah et al. (2008) and Greenberg et al. (2006), all of which and create a large amount of heat, which must be removed from the ICT components at a rate sufficient to avoid serious overheating problems and system failures (Sahin et al., 2005). More than 30% of the heat removal costs of a typical data centre is used in IT equipment and cooling equipment. Thus, an important part of a server is the heat sink that is set over the CPU (Dai et al., 2014), as shown in Fig. 1.

The thermal effect can cause a failure of mechanisms in electronic component devices, due to metal migration, void formation, and inter-metallic growth. Actually, one of the common factors that control the reliability of electronic products is the maximum temperature limitation of these devices. For each 10oC increase above the critical operating temperature (~85°C) of high-power electronics, the rate of these failures almost doubles (Gurrum et al., 2004). Therefore, electronics thermal management is a crucial significance, as it is reflected in the market (Mostafavi, 2012). Another important factor is the increase of the cost of thermal management products, which went from nearly $7.5 billion in 2010 to $8 billion in 2011, and is predicted to reach $10.9 billion by 2016; the annual rate of increase is 6.4%. Fans and heat sinks (HSs) as thermal management hardware components take an 84% share of the total market. However, software, interface materials, and substrates as the other main cooling products account for between 4% and 6% of the market (BCC Research, 2014).

From the above discussion, there is a challenge to reject high heat flux caused by efficient and small electronics. Many ways to remove the heat from electronics. However, two common ways are used widely that either geometry modifications or using advanced fluids such as nanofluids, or it can be a combination of both ways (Al-Asadi et al., 2017 & 2016). Geometry modifications of heat sink can be extended surface area such as using ribs and grooves (Al-Asadi et al., 2017, 2016 & 2013) or perforation techniques such as perforated pinned HSs (Al-damook et al. 2016 and Al-Sallami et al. 2016) and perforated strip fins HSs (Al-Sallami et al. 2017). Using advanced fluid such as nanofluids also can improve the heat transfer, but significantly increase the pressure penalty (Al-Asadi et al., 2017 & 2018). Very effective mechanism to enhance the heat transfer is forced convection heat transfer mechanism in heat sinks (Fig.

2). The process starts when the generated heat by electronic component is conducted to the heat sink base through the super conductive sticker. The heat is conducted through the heat sink from the base to the fins by conduction heat transfer. After that, a convection heat transfer is started between fins and the cooling fluid. The process is thus called conjugate heat transfer since both conduction and convection process are occurring simultaneously. Lastly, the cooling fluid can be either air or liquid when in the former case the heat sink is called air cooled sink while in the latter case it is called liquid cooled heat sink (Cengel, 2006).

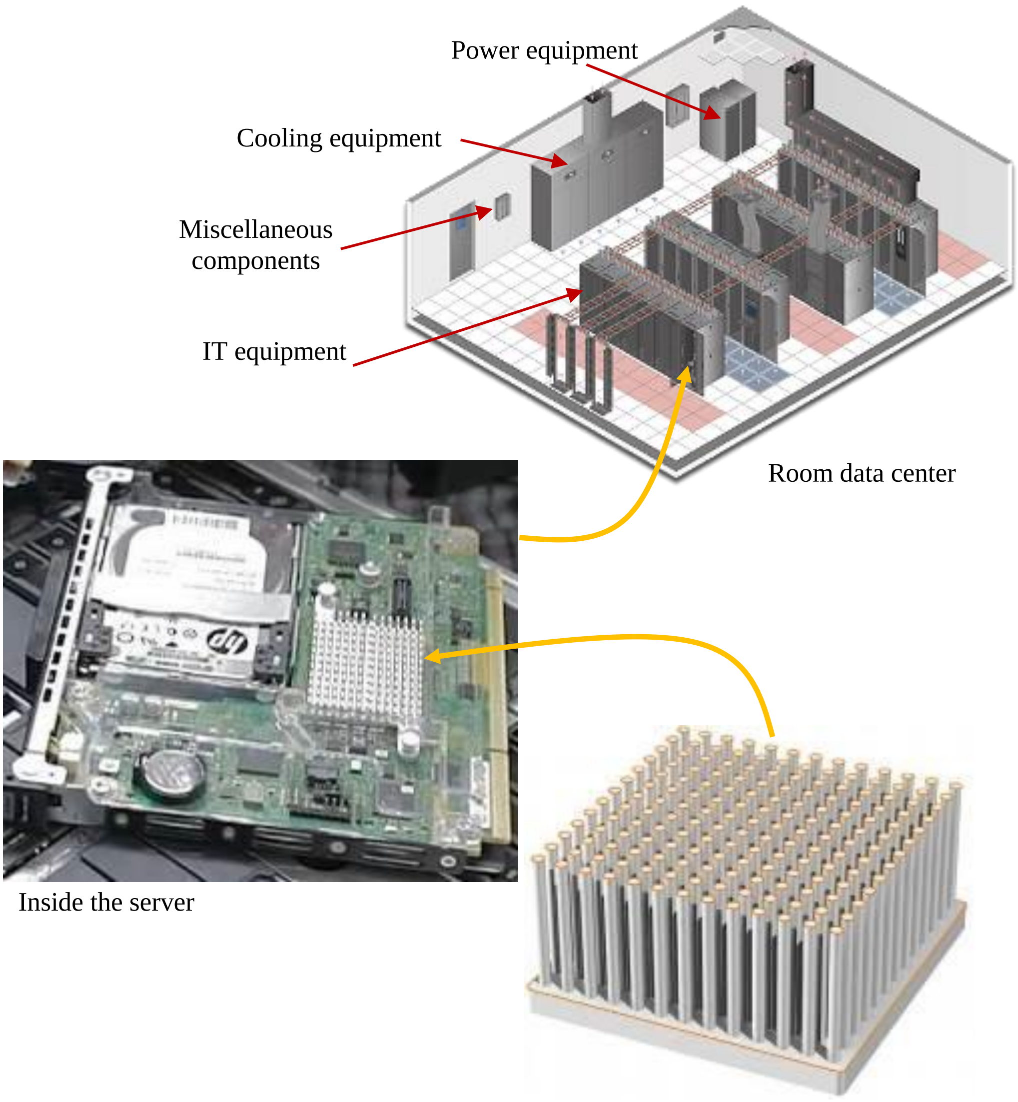

Fig. 1I: Data centre infrastructure (Tripplite, 2012), server (DeepInIt, 2013), and pinned heat sink (Alutronic, 2015)

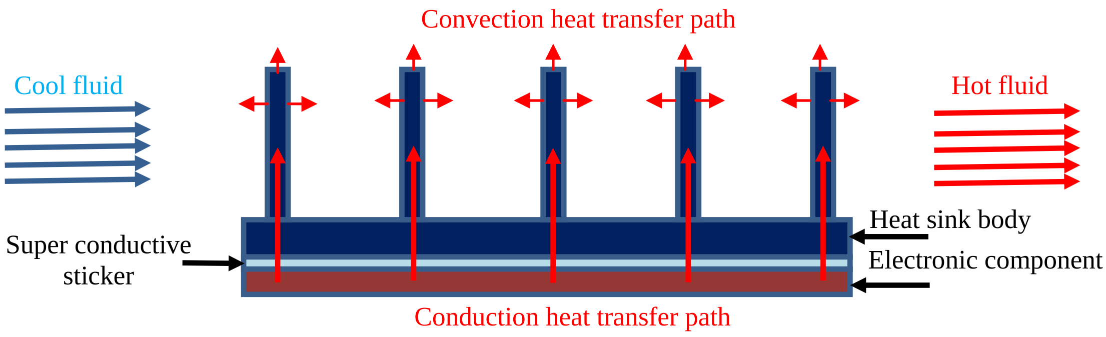

Fig. 2: The heat transfer mechanism in the forced convection heat sinks.

II. INTRODUCTION TO HEAT SINK TECHNOLOGY

Finned heat sinks are classified into two main types: plate fin heat sinks (PFHSs) and pin heat sinks or pinned heat sinks (PHSs), as shown in Fig. 3. Such heat sinks are manufactured and produced by several companies, both large and small, such as Airedale in the UK, Raypak in the USA, to name of few. A set of base tube materials that have high thermal conductivity, such as copper and aluminium, can be employed to manufacture heat sinks depending on their cost and ease of manufacturing. In recent years, the technology relating to heat sinks designed for cooling electronics has become widespread and familiar, since their initial cost is low, and they are simple to install and have a reliable manufacturing process (Chingulpitak, 2015).

A rectangular fin with high length to width ration; by far higher than one, is called plate fin. The length of the fin is always equal to the length of the heat sink while the width can be varied. It is a very common design due to its easy manufacturing process. In addition, this type exhibits a lower pressure drop and higher surface area than pinned heat sink design. However, the continuous growth of the boundary layer with the fin length leads to reduce the heat dissipation rate.

Pinned heat sinks are proposed to break the growth of the boundary layer and enhance air turbulence to increase the heat dissipation rate. In general, pin fin layouts are made up of a network of solid pins mounted directly on the heat sink surface. Either a staggered or an in-line arrangement is usually configured for arrays of pins with the working fluid flowing parallel or perpendicular to the pin axes. Pin morphology has an important function in manufacturing and heat transfer characteristics. Cylindrical, rectangular, square, elliptic, and conical or semi-conical are the widespread uniform pin fins geometries. Each morphology exhibits unique features, for instance; circular pin fin showed lower pressure drop than square one when both showed comparable heat dissipation rate (Al-Sallami et al. 2016).

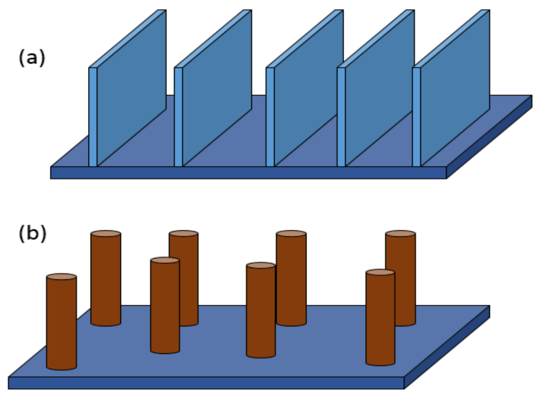

Fig. 3: (a) Plate fin heat sink design and (b) pinned heat sink design (circular type).

III. IMPORTANCE OF ELECTRONICS COOLING

In many engineering applications, the power dissipation creates heat as a by-product, which may cause system failure in these devices due to serious overheating. This is mainly due to the certain temperature limits that are required for almost all applications to work in suitable conditions. Currently, as electronic devices decrease in size, their thermal power losses increase (Mostafavi, 2012). Additionally, the forced convection of heat sinks covers a wide range of industrial applications in order to overcome the damaging effects of overheating or burning. Hence, it is very important to consider the cooling system for electronic components.

The main industrial applications of heat sinks are cooling of tiny electronic components, electronic boards and components, the central processing unit (CPU) of personal computers and data centres, sophisticated electronic chips, electrical appliances (computer power supplies, substation transformers, etc.), the aerospace industry, and cooling of fuel elements in nuclear reactors (Prashanta, 1998; Sahin & Demir, 2008a; Sahin & Demir, 2008b; Amol & Farkade, 2013; Sara et al., 2000; Sara et al., 2001).

Plate and pin fins are commonly used for cooling the CPUs of a personal computer and electronic components devices (Dempong, 2001; Kim & Kim, 2009; Yakut et al., 2006a; Zhang et al., 2005; Yakut et al., 2006b; Naphon & Knonseur, 2009); Naphon & Wiriyasart, 2009; Naphon & Wonwises, 2010; Naphon, 2011; Konsue, 2012; Diani et al. (2013), integrated circuit chips in electronic equipment, compact heat exchangers, and cooling of advanced gas turbine blades (Jonsson & Moshfegh, 2001; Yang et al., 2007; Jeng & Tzeng, 2007; Sahin et al., 2005).

Based on the aforementioned, the fin perforations plays an important role in the thermal airflow through heat sinks; in other words, the cooling performance will be enhanced and the pressure drop will be reduced. It is possible those heat sinks are useful for cooling electronic applications and for IC engine cooling such as substation transformers, computer power supply, and fins in a car radiator (Prashanta, 1998, Sahin & Demir, 2008a; Sahin & Demir, 2008b; Amol & Farkade, 2013; Sara et al., 2000; & Sara et al., 2001).

IV. LIQUID AND AIR COOLING OF DATA CENTRES

Generally, there is a temperature limit to operate any electronic device which is up to 85oC. Therefore, the electronic systems in data centres should be cooled by either liquid or air (Anandan & Ramaligam, 2008) to keep the temperature below 85oC (Gurrum et al., 2004 & Al-damook et al, 2018).

Liquid cooling such as water, nanofluids, polymers, and dielectric liquid (Hydrofluoroethers, HFE) can be used to cool the heat sinks and servers of racks in data centres. Direct contact liquid cooling techniques, such as immersing servers into dielectric liquid (Tuma, 2010; Almaneea, 2014) may be used. Ramifications of immersion in data centre cooling and energy performance can be found in Chi et al (2014). Another technique to cool data centres is indirect contact liquid cooling via bringing the cooled liquid to heat sinks on the top of the chips or alternatively to the rack or into the server as a heat exchanger on the front or rear of the rack (Villa, 2006). The main advantages of this method are the heat transfer rate enhancement is greater than that of the air-cooling method since the thermal conductivity and thermal capacity of liquids are superior to those of air. In addition, dielectric liquids act as electrical insulators without any electrical discharge (Naidu & Kamaraju, 2013; Alkasmoul, 2015). However, the main disadvantages of liquid heat sinks are: they exhibit higher pressure drop than air cooled one because the viscosity and density of liquids are larger than air, liquid cooling is risk due to the probability of liquid leaking, which may damage the server's electronic components, resulting in data centre loss; the risk of condensation forming, which may lead to a failure in the system, the high cost of maintenance and installation and an increase in the required infrastructure such as pipe work includes leak detection, and installation of insulation (Villa, 2006; Naidu & Kamaraju, 2013).

Due to all the above disadvantages of liquid cooling, the most common method of heat dissipation for thermal control of electronics is air cooling. Reduced cost, the availability of air, and the simplicity of design are the main benefits of this cooling method. As an example of an active air-cooled device, heat sinks with a fan or blower are commonly employed. An amount of heat is dissipated from the heat source to environmental air utilising a heat sink as a heat exchanger, which is a vital practice employed in air-cooling systems. This transfer mechanism is easy, simple and leads to a reduced cost (McMillin, 2007). However, the heat transfer rate of the air-cooling method is lower than that of the liquid cooling, as indicated previously.

In the technique of air cooling, the heat transfer rate of the heat sink can be augmented, either by increasing the fan speed or the surface area of the heat sink. As the fan speed increases, however, the fan's reliability reduces and power consumption is significantly increased and the noise level increases to undesirable levels, particularly for the office or home consumer. Increasing the temperature is also unacceptable because it reduces the reliability of the central processing units (CPUs) and that leads to earlier chip short circuit (McMillin, 2007). Hence, increasing fan speed and increasing the temperature are not a favoured approach. Thus, increasing surface area will enhance the heat dissipation rate under constant fan speed and heat sink temperature, but with a noticeable increase in pressure penalty.

V. PERFORATED FIN HEAT SINKS (PFHSs)

The main reason for interest in this subject is that forced convection fins have various applications, from the cooling of tiny electronic components to cooling of fuel elements in nuclear reactors. Furthermore, according to the author's knowledge and the next literature reviews in this section, fin perforations plays an important role by way of improving the thermal-hydraulic characteristics of heat sinks and vanishing the vortexes and boundary layers behind solid plate fins and pinned heat sinks. In addition, devices with these perforated fins will be lighter in weight and material will also be saved in their design (Yaghoubi et al., 2009). Only air is used as a coolant in the following works.

The numerical studies calculated Nu_T based on the total wetted surface area of the perforated fins is lower than that of solid fins heat sink. Hence, we recommend determining the projected Nusselt number (Nu_P), based on surface area of only the heat sink base, L×W: where L, and W are length and width of the heat sink, respectively, as this may be a more effective measure of cooling capacity for a given heat sink size. The CPU temperature should not exceed the reference critical temperature of 85^{o}C (Gurrum et al., 2004; Al-damook et al., 2018). Furthermore, it should be considered to minimise CPU temperature and fan power consumption in order to select the optimum heat sink design. Thus, it can be classified into three main types perforated plate fin heat sinks (PPFHSs), perforated folded fin heat sinks (PFFHSs) and perforated pinned heat sinks (PPHSs).

VI. PERFORATED PLATE FIN HEAT SINKS

Either perforation can be along the length of the plate fins as a small channel (frontal perforations) Fig. 4 (a), or on the side of the plate fins as lateral perforations, Fig. 4 (b). They are able to enhance thermal airflow of these heat sinks compared to the equivalent solid fin heat sinks.

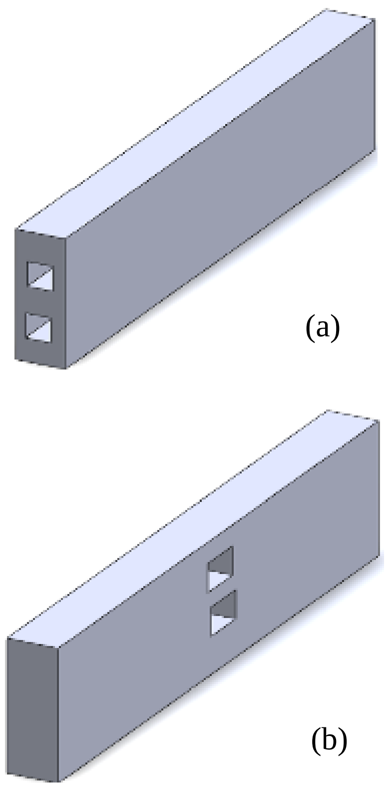

Fig. 4: (a) plate fins with frontal perforations and (b) plate fins with lateral perforations

A. Plate Fins with Lateral Perforations

The first section deals with several experimental reports on lateral circular perforated plate fin heat sinks. The main conclusion is that the Nusselt number and friction factor of perforated plate fins are larger than those of the solid fins. For instance, Dhanawade et al. (2010, 2014, and 2014) have produced three studies on lateral perforation PFHSs. The first one investigates the effect of lateral circular perforated plate fins on forced convection heat transfer (Dhanawade & Dhanawade, 2010), and found that, at low applied heat flux levels up to 14000W/m^2, the Nusselt number for the 12mm perforation diameter is larger than that for the 10mm perforation diameter. However, at high heat flux levels up to 20000W/m^2, the largest Nusselt number is for the 10mm perforation diameter.

Ganorkar & Kriplani (2012) produced another study explaining the effect of the lateral circular perforated plate fins on the heat transfer rate. This kind of HS is used to cool electronic applications and in IC engine cooling such as a substation transformer, computer power supply, and fins in a car radiator. The effects of the lateral perforated plate fins' shape on forced convection heat transfer and friction factor (*f*) are investigated in another report by Dhanawade et al. (2014). Evidently, the data point out that the *Nu* and *f* of the perforated fins are higher compared to solid fins and they increase with increases in the perforations' diameter. The effectiveness of the square perforated fins, $\frac{Q_{perforated\ fins}-Q_{solid\ fins}}{Q_{solid\ fins}}$, is nearly the same as that of the circular perforated fins, while, with respect to the friction factor, the circular perforated fins have the lowest value. Dhanawade et al. (2014) have developed their previous work utilising the Taguchi design experimental method for optimum design of the thermal performance of circular lateral perforated PFHSs. They found that the most vital parameters are *Re*, perforation porosity, and then fin thickness, respectively. The highest level of effectiveness for the perforated fins is nearly 19%, noted at *Re*=87000, 0.22 porosity, and 5mm of fin thickness. The findings show agreement with the results of Ganorkar & Kriplani (2012).

According to numerical studies, several factors such as average friction factor, a Nusselt number based on the total wetted surface area (Nu_T), and fin weight reduce as increasing the number of perforations. However, the percentage of heat transfer enhancement or fin effectiveness ($\varepsilon=q_{with\ fins}/q_{without\ fins}$) decreases incrementally with the number of perforations up to eight holes and then this enhancement increases as the perforations rise up to 50 holes, according to work by Yaghoubi et al. (2009) and Shaeri, et al. (2009). They investigated thermal and airflow characteristics of square lateral perforated PFHSs at variable porosity under laminar and turbulent airflow. Under the laminar flow conditions, the perforated fins effectiveness is nearly the same value as that of the solid fins, even though the perforations have increased in number, whereas, for the turbulent flow, heat transfer rate increases when increasing the number of perforations

B. Plate Fins with Longitudinal (Frontal) Perforations

The thermal and hydraulic characteristics of perforated plate fin HSs have only been numerically reported with laminar and turbulent airflow; there is no experimental work. Either *k-ε* standard or RNG models are utilised in the following literature to solve the governing equations. Similarly to lateral perforation plate fins, total drag (friction and pressure drag), a Nusselt number based on the total wetted surface area (Nu_T) and the weight of the fins reduce as the number of these longitudinal perforations along the length of the plate fins increases. Fin effectiveness is enhanced via these perforations, which alleviate the recirculation zones that are existed behind the plate fins for both laminar and turbulent airflow. For example, Shaeri & colleagues (2009 and 2012) have presented work related to the perforated PFHSs in the presence of laminar and turbulent airflow.

The laminar flow and heat transfer characteristics have been numerically investigated by the following researchers.

The effects of the number of perforations with variable porosity on the heat transfer rate and laminar airflow have been investigated by Shaeri & Yaghoubi (2009). Numerical data explain that the average friction coefficient, pressure drop, average Nusselt number (Nu_T) and the weight of the fins decrease, but the effectiveness of the perforated fins increases when the number of perforations increases. Perforated plate fins reduce the shape and the size of recirculation zones (wakes) behind these fins compared with solid fins. The effects of size and number of perforations of a flat plate of the same porosity on thermal performance and laminar airflow have been studied by Shaeri & Jen (2012). The outcomes illustrate that the total drag, friction and pressure drag stay nearly constant for all kinds of perforated and solid fins because the airflow has a low velocity inside those perforations. Conversely, the thermal entrance length (the distance of thermal boundary layer inside the perforations) is smaller with a larger number of perforations than with a smaller number perforations, by which means the heat transfer rate of fins with a smaller number of perforations (larger perforation sizes) improves by approximately 80% compared with solid fins.

The following researchers report turbulent airflow and heat transfer characteristics numerically.

Shaeri & Yaghoubi (2009) have reported the influence of perforations with a variable porosity in perforated plate fins on the heat transfer rate and turbulent airflow. The results indicate that the rising number of perforations influences: the size of the wakes that from behind the fin; the length of the recirculation zone around the lateral surfaces of the fin; total drag; skin friction coefficient; and the weight of the fins decreases. Fin effectiveness of perforated fins with three perforations is almost 65% higher than that of the solid fin. On the other hand, Shaeri & Jen (2012) report the effects of size and number of perforations for the same porosity on thermal performance and level of turbulent fluid flow. The results prove that the friction drag of the perforated fins is higher but the pressure drag and the total drag of the perforated fins are smaller than those of the solid fins. Furthermore, fin effectiveness increases with increasing number of perforations; in other words, heat transfer rate enhances with decreases in perforation size at constant porosity

C. Effect of Differently Shaped Perforations

Concerning the shape of the perforations along the plate fins, Ismail et al. (2013 and 2014) have only numerically investigated the effect of shape with laminar and turbulent airflow.

The effects of circular and square perforations along the plate fins on the thermal and turbulent airflow performance have been considered by Ismail et al. (2013). The results show that the heat transfer rate of the perforated fins is nearly the same for both the circular and square perforations, while the pressure drop is lower for the circular perforated fins. In addition, as the number of perforations increases from two to three, fin effectiveness is almost the same but pressure drop decreases. Ismail et al. (2013 and 2014) have developed this study via considering more perforation shapes in an investigation into the effects of perforation shapes on the thermal and hydraulic performance under laminar and turbulent airflow. Circular, square, triangular, and hexagonal perforation shapes have the same surface area, as shown in Fig. 5. Commonly, the results are the same for both laminar and turbulent airflow. The hexagonal and circular perforations have higher heat transfer performance enhancement (HTPE) and lower pressure drag coefficient than the other perforations, Fig. 6. In addition, the maximum Nusselt number, Nu_T, still occurs for the solid plate fins.

According to the shapes of the fins with lateral perforations, Ismail et al. (2014) have demonstrated the effects of number and shape of lateral perforations, circular, square, triangular, and hexagonal, on the turbulent airflow and heat transfer. RANS-based modified *k-ω* turbulent flow has been considered. They indicate that the shapes of the perforations have a significant role in enhancing the cooling and hydraulic performance. Hexagonal perforated fins, however, have the largest effectiveness and heat transfer performance enhancement (HTPE) of the perforated fins. As indicated earlier, solid fins have the maximum Nusselt number, Nu_T, and the largest friction coefficient and this decreases with increasing in the number of perforations.

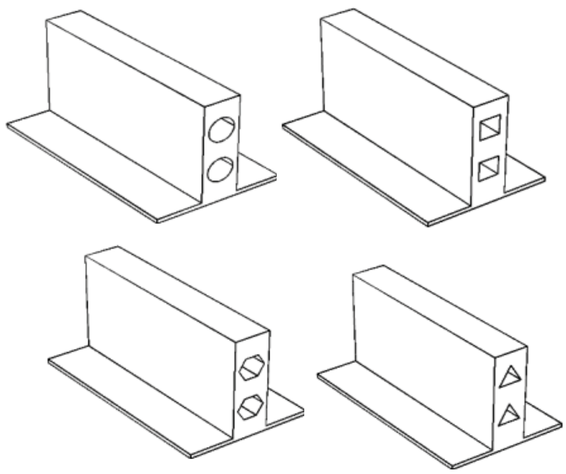

Fig. 5: Different sorts of perforated FHSs: circular, square, hexagonal, and triangular (Ismail et al., 2013)

Very recently, Al-Sallami et al., 2017 conducted a numerical study to investigate the effect of various perforations' geometries on the thermal-hydraulic performance of plate fin, as shown in Fig. 7. The results revealed that the increasing of perforation area cross section results in an enhancement in both thermal and hydraulic performance of the examined fins.

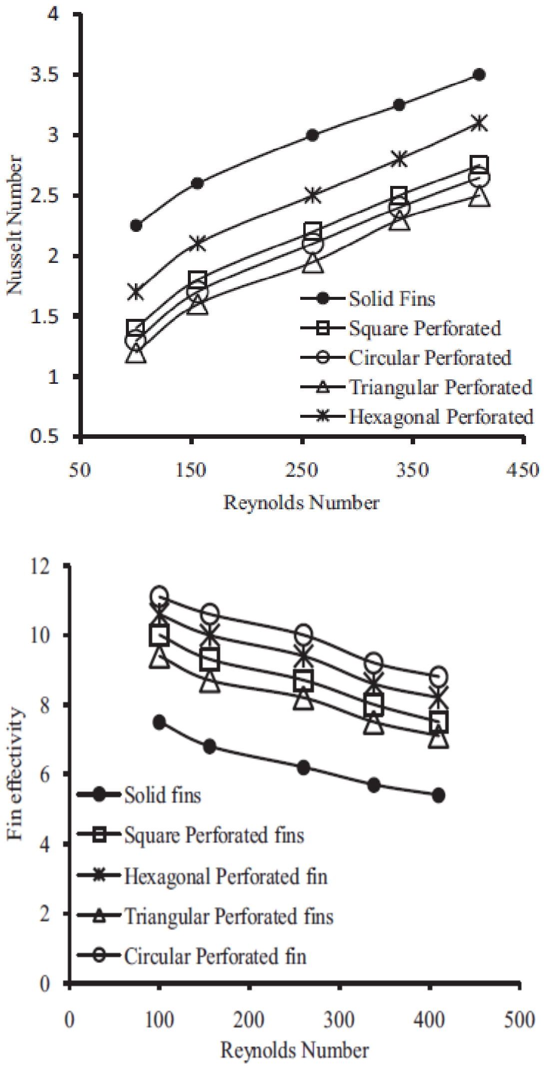

Fig. 6: Nusselt number and fin effectivity variations for different types of fin (Ismail, 2013)

D. *Perforated Ribs and Blocks as Fins*

The experimental testing of the other types of perforated blocks as fin heat sinks, ribs or baffles towards the flow direction is demonstrated in this section. These perforations have differently shaped perforations. For instance, turbulent forced convection heat transfer and friction loss of a single baffle that has been perforated in different positions, of different sizes, and with inclined orientations inside the rectangular channel have been investigated by Dutta and Dutta (1998). The results point out that both local and average Nusselt numbers increase when increasing the angle of baffle orientation and baffle size, and with a decreasing number of circular perforations. With regard to the position of the baffle, when it is located at the start from the heat source, the Nusselt number is higher than that of the baffle, which is placed far away of the heat source. Furthermore, the friction factor ratio decreases as the angle of baffle decreases and circular perforation density increases.

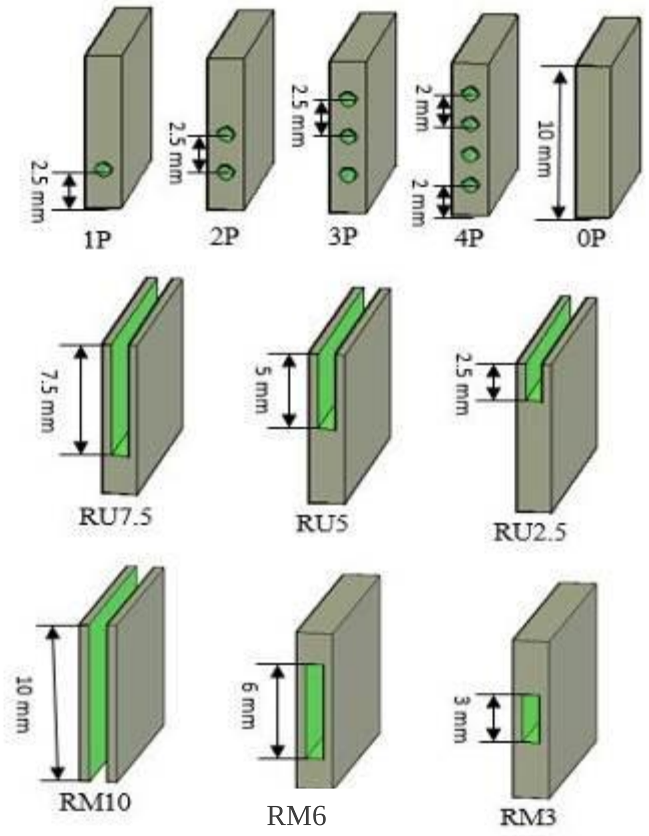

Fig. 7: different design of perforated plate fins heat sinks (Al-Sallami et al. 2017)

Sara et al. (2000 and 2001) have produced two works related to solid and perforated blocks, which are used in many practical applications. These works are focused on the thermal performance efficiency (η=h_a/h_s, where h_a and h_s are the convective heat transfer coefficient with and without blocks, respectively) of these perforated block types with turbulent airflow, Fig. 8. The results show that the performance efficiency and Nusselt number of the perforated blocks are greater than the solid blocks and they increase by nearly 30%-60% as increasing the perforation inclination angle, perforation open-area ratio, and perforation diameter. Additionally, friction factor and pressure drop of the perforated blocks are lower than those of the solid ones. Therefore, the gained energy performance of the perforated blocks compared to the solid blocks is up to nearly 77% due to the enhanced Nusselt number and the reduced pressure drop of the perforated blocks.

With respect to numerical reports of perforated ribs as fins, it is indicated that the numerical data are in agreement with the previous experimental reports. For example, Khoshnevis et al. (2009a) studied the effects of circular perforated ribs with various attack angles towards the flow direction on the thermal airflow of heat sinks inside a rectangular channel. However, the effects of two kinds of perforation, circular and slotted perforated ribs shown in Fig. 9, were reported in another study by Khoshnevis et al. (2009b). The Nusselt number enhances as the perforation inclination angles, perforation diameter and perforation open-area ratio increase. Furthermore, pressure drop reduces with increasing perforation diameter and open-area ratio, but it is not affected by perforation inclination angles. Generally, the Nusselt number and pressure drop of the perforated ribs are slightly enhanced compared to slotted ribs with the same open-area ratio.

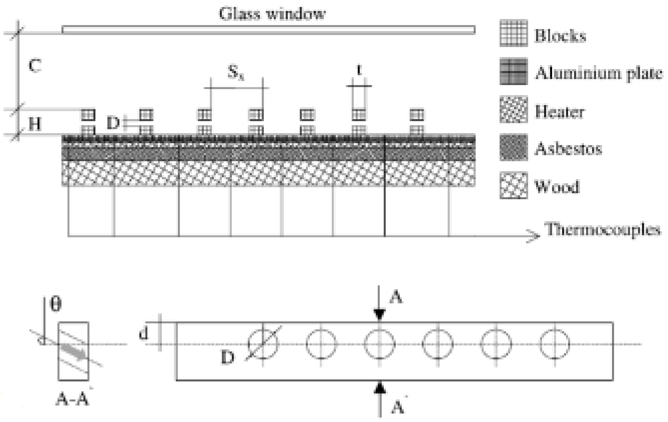

Fig. 8: The test section of perforated blocks/ribs with different views (Sara et al., 2001)

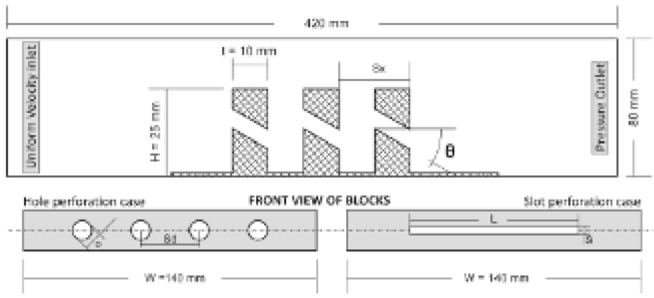

Fig. 9: The angle of perforations and slots in rectangular blocks towards flow directions (Khoshnevis et al., 2009b).

VII. PERFORATED FOLDED FIN HEAT SINKS (PFFHSs)

The thermal resistance of several triangular folded fin heat sinks is investigated by Jia et al. (2003, 2004 and 2007). The fin types are: extruded plate fin (a model), slit folded fin (b model), perforated folded fin (c model), and perforated slit folded fin (d model), as shown in Fig. 10, and they are tested for the same boundary conditions such as applied heat flux, inlet air velocities and inlet air temperature. The experimental results indicated that the thermal resistance of the new triangular folded fins design (b, c, and d models) is superior to that of the traditional plate fins (a model). The most effective for application in high-powered electronic devices are the slit folded fin (b model) and/or perforated slit folded fin (d model) heat sink models. The thermal resistance of the slit folded fin (b model) and the perforated slit folded fin (d model) is nearly 18% and 20% respectively less than that of conventional plate fin heat sinks (a model) at a fixed fan power. In addition, the cooling performance of these heat sinks depends remarkably on the increasing fin height, a number of slits for the perforated slit folded fin, decreasing fin pitch, and Reynolds number.

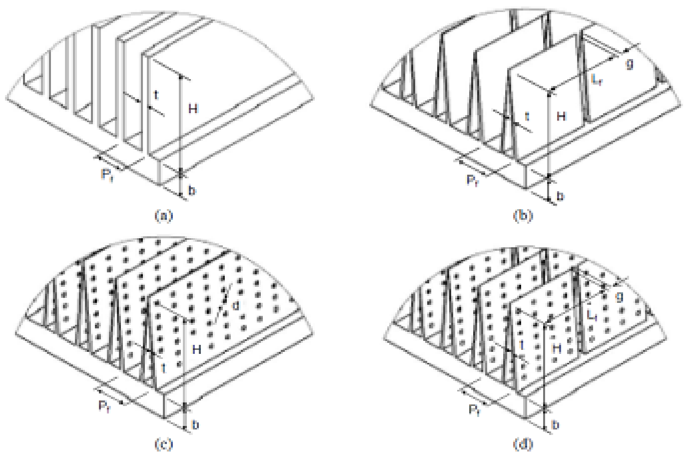

Fig. 10: Different designs of folded fin heat sinks: (a) Extruded plate fin, (b) Slit folded fin, (c) Perforated folded fin, (d) Perforated slit (Jia et al., 2003)

VIII. PERFORATED PINNED HEAT SINKS (PPHSs)

Relatively few studies have considered the effect of perforations on the heat transfer and pressure drop of perforated pinned heat sinks (PPHSs), shown in Fig. 11 which is investigated experimentally in the following literature survey, rather than through numerical reports. It is indicated that pin perforations offer considerable benefits by enabling the heat transfer to be improved while at the same time reducing both the pressure drop across the heat sink and the fan power required to pump the air through it. In addition, reduction in the weight of the pinned heat sink can be obtained via these perforations. These perforated PHSs can be classified into two types, single and multiple perforations.

A. *Single Perforated Pinned HSs*

PHSs with only one perforation are called single perforated PHSs, as shown in Fig. 11. The effects of square and circular cross-section perforated pinned heat sinks in an in-line array have been reported by Sahin & Demir (2008a and 2008b), while Amol & Farkade (2013) considered the effect of a staggered arrangement of circular cross-section perforated pinned heat sinks. The various parameters with Reynolds number, such as turbulent airflow, clearance ratio (*C/H*) and inter-fin spacing ratio (streamwise distance) in the flow direction, were studied in these three reports to investigate the Nusselt number and pressure drop of perforated pinned HSs where *C* is the distance from the tip of the pins to the upper surface of the wind tunnel, and *H* is the height of the pins. In addition, this perforation is just a single circular perforation located near the bottom of the fin. These studies have found consistently that a single perforation leads to an enhancement of Nusselt number and a reduction in pressure drop compared to the equivalent solid pin system, as shown in Fig. 12. For example, Sahin & Demir (2008a) have found that the enhancement efficiencies of square cross-section perforated pinned heat sinks vary between 1.1 and 1.9, while the enhancement efficiencies of circular cross-section perforated pinned heat sinks are the highest, varying from 1.4 to 2.6 depending on the inter-fin spacing ratio and clearance ratio (Sahin & Demir, 2008b). In addition, the projected Nusselt number, $Nu_{P,}$ is enhanced and the friction factor increases when reducing both clearance ratio (*C/H*) and streamwise distance.

It can be concluded that the main outcomes of this design are that localised jet flows through the perforations increase local heat transfer by alleviating the recirculation zones that from behind solid pins, and increasing shear-induced mixing leads to enhance thermal airflow and reduce the pressure drop through perforated pinned heat sinks. To select the optimum design, the Taguchi experimental design method design is used in these studies utilising the ANOVA-TM software package to evaluate the effect of each parameter on the optimisation criterion. The trade-offs among goals are considered and the optimum design occurs as pin height and pitch are 50mm and 3.417, respectively at *Re*=42000 (Sahin & Demir, 2008).

As indicated in the previous three studies, the perforated pinned heat sinks can be used for large heat exchange applications because the dimensions of the heat sink are 250×250mm, which is large, and the aspect ratio of height to diameter, *H/d*, is greater than four (Vanfossen & Brigham, 1984). However, it is difficult to apply this size of perforated PHSs for cooling electronics systems due to restrictions in the size of these systems. Thus, a mini-perforated pinned heat sink design is required to enhance heat transfer rate and at the same time reduce fan power consumption to drive air through PHSs, and that leads to the desirable benefit of reducing the CPU temperatures of the heat sink in the case of a fixed heat sink size.

B. *Multiple Perforated Pinned HSs*

Based on the literature review and our knowledge, the combination of experimental and numerical studies relating to the benefits of single and multiple perforated pinned heat sinks for electronic cooling applications has not yet been reported. Hence, illustrating the comprehensive thermal airflow of this kind of heat sink has motivated a full study of the benefits of multiple perforated PHSs, as shown in previous Fig. 13.

The expected benefits of multiple pin perforations may enhance the heat transfer rate (increasing Nu_T and Nu_P) while reducing the fan power consumption, which is required to overcome the pressure drop across the heat sink. The minimisation of CPU temperature and thermal resistance are the other important factors for thermal management of systems containing electronic components, together with minimising the fan power consumption. The additional benefit of a reduction in the weight of the pinned heat sinks is important to reduce the cost and save material.

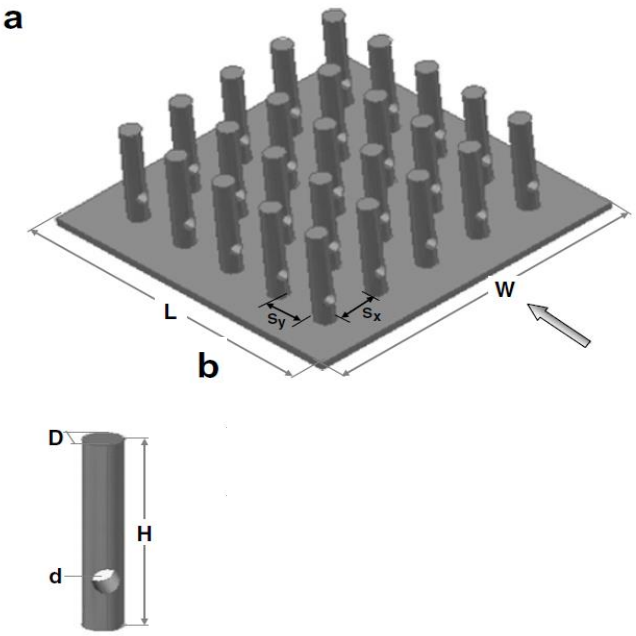

Fig. 11: (a) Perspective view of the heat exchanger and a single perforated pin configuration (b) Sectional view of heating unit and tested model assembly (Sahin & Demir, 2008b)

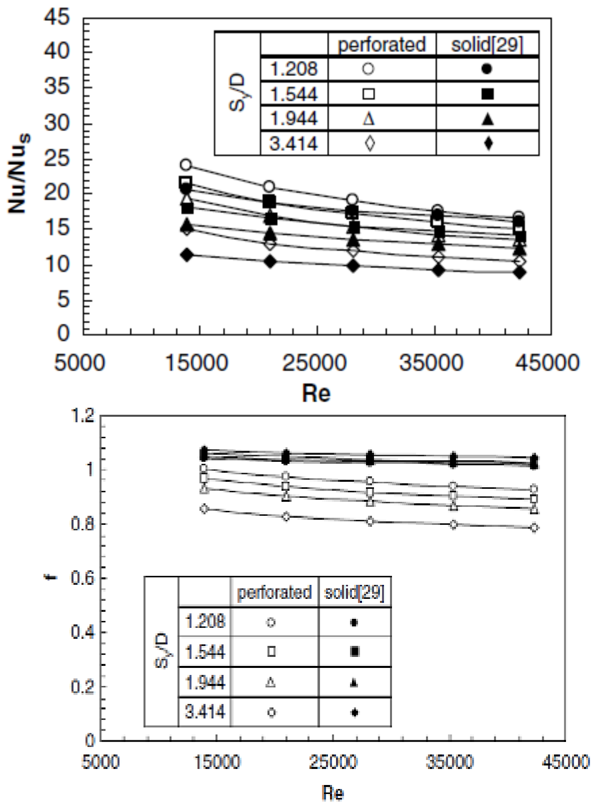

Fig. 12: Nusselt number and friction factor variations for single perforated pin fins (Sahin & Demir, 2008b)

Al-Damook et al. (2015) have very recently used complementary experimental and numerical methods to explore the benefits of using multiple pin perforations within PHSs for the first time. They showed that the heat transfer rate increases monotonically with the number of pin perforations, while the pressure drop and fan power, required to overcome the pressure drop, both reduce monotonically; the location of the perforations were found to be much less influential. Pins with five perforations were found to increase the heat transfer rate by over 10%, and reduce pressure drop by over 15%, compared with corresponding solid pin cases. These benefits are due not only to the increased surface area but also caused by the interactions of localised air jets through the perforations. Their conjugate heat transfer analysis showed, further, that improved heat transfer with pin perforations leads to significantly reduced processor case temperatures with the additional benefit of a reduction in the weight of the pins. Their experiments also revealed that practical considerations, including pin perforation alignment with the dominant flow direction and the quality of the pins' surface finish, can affect the heat transfer and pressure drop significantly. The effect of variable air properties on the heat transfer and pressure drop of perforated pinned HSs have been investigated by Al-Damook et al. (2016). They found that the pressure drop increases while the heat transfer rate reduces due to increasing air viscosity with temperature. Thus, it is recommended the effect of variable air properties is considered for future the hydrothermal of heat sink simulations studies.

While Al-Sallami et al. (2017) extended this work to consider the benefits of multiple perforations and fin arrangement for heat sinks with strip fins, Fig. 14. However, as in previous numerical simulations of thermal air flows over heat sinks, both studies ignored the variation in air flow properties that inevitably results from the temperature variation across heat sinks and proposed that the discrepancies of up to 15% that they found between their experimental measurements and numerical predictions may be due to the practical difficulties of achieving exact perforation alignment and additional thermal resistance and surface roughness induced during the manufacturing process.

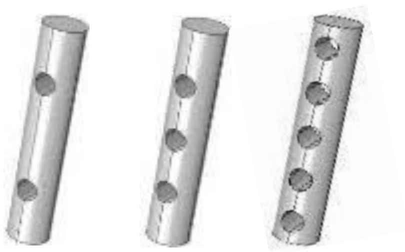

Fig. 13: a multiple perforated pinned heat sinks (Al-Damook et al. 2015)

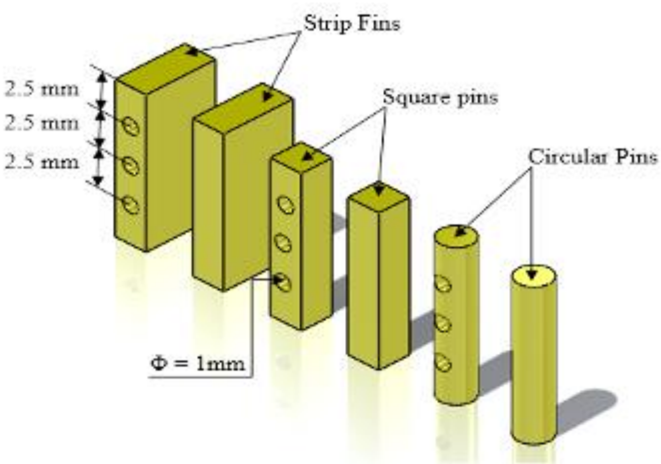

Fig. 14: Different strip fin and pin heat sinks designs (Al-Sallami et al. 2017)

IX. Conclusions and Recommendation for Future Works

A critical review has been conducted in this study and the following conclusions and recommendations have been obtained:

1. The use of perforations decreases pressure drop. This decrease is increasing with the increase of fluid velocity due to the reduction of the role of frictional pressure drop and the increase of the role of drag pressure drop.
2. The use of perforations enhances the heat dissipation rate significantly due to the increase of heat transfer area, a decrease of the dead zone behind fins and the increase of air turbulence in pinned heat sinks.
3. In addition, the mass of heat sink is reduced which means less material will be consumed to manufacture perforated heat sinks in comparison with solid designs.
4. For Numerical studies, the effect of variable air properties is recommended to investigate the hydrothermal of heat sink simulations for future studies.
5. However, the manufacturing process of perforated designs is more complex than solid ones. This issue can be terminated with the quick advance in 3D printers that makes the manufacturing of complex geometries feasible.

Besides, despite a large number of previous studies that have conducted in the literature to investigate the thermal-hydraulic performance of perforated heat sinks. A few more studies are still needed to be conducted to fill some few gaps that should be filled, as follow:

1. For laminar flow, lateral perforations plate fin heat sinks.
2. For laminar and turbulent flow, perforated cross-cut FHSs, and the number and shape of perforations pin FHSs.
3. The number and shape of perforations plate FHSs as an experimental laminar and turbulent flow to verify the previous numerical works.
4. For all kind of previous perforated fins, another coolant as water, nanofluid, and 3M Novec fluid are recommend to be used.

It is required more detail for porous pin and plate fin heat sinks.

X. References

Al-Asadi, M.T., A. Al-damook, and M.C.T. Wilson, Assessment of vortex generator shapes and pin fin perforations for enhancing water-based heat sink performance. International Communications in Heat and Mass Transfer, 2018. 91: p. 1-10.

Al-Asadi, M.T., Mohammed, H.A., Kherbeet, A.S. and Al-Aswadi, A.A., 2017. Numerical study of assisting and opposing mixed convective nanofluid flows in an inclined circular pipe. International Communications in Heat and Mass Transfer, 85, pp.81-91.

Al-Asadi, M.T., F.S. Alkasmoul, and M.C.T. Wilson, Heat transfer enhancement in a micro-channel cooling system using cylindrical vortex generators. International Communications in Heat and Mass Transfer, 2016. 74: p. 40-47.

Al-Asadi, M.T., F.S. Alkasmoul, and M.C.T. Wilson, Benefits of spanwise gaps in cylindrical vortex generators for conjugate heat transfer enhancement in micro-channels. Applied Thermal Engineering, 2017.

Al-Asadi, M.T., Mohammed, H.A., Akhtar, S.N., Kherbeet, A.S. and Dawood, H.K., 2017. Heat transfer enhancements using traditional fluids and nanofluids in pipes with different orientations: a review. Journal of Nanofluids, 6(6), pp.987-1007.

Al-Asadi, M.T., and M.C.T. Wilson, Evaluation of nanofluid performance with vortex generators for enhanced micro-channel heat transfer. Eleven International Conference on Thermal Engineering: Theory and Applications February 25-28, 2018, Doha, Qatar, 2018.

Al-Asadi, M.T., A. Al-damook, and M.C.T. Wilson, Assessment of vortex generator shapes and pin fin perforations for enhancing water-based heat sink performance. International Communications in Heat and Mass Transfer, 2018. 91: p. 1-10.

Al-Asadi, M.T., and M.C.T. Wilson, Evaluation of nanofluid performance with vortex generators for enhanced micro-channel heat transfer. Eleven International Conference on Thermal Engineering: Theory and Applications February 25-28, 2018, Doha, Qatar, 2018.

Al-Asadi, M.T., F.S. Alkasmoul, and M.C.T. Wilson, Benefits of spanwise gaps in cylindrical vortex generators for conjugate heat transfer enhancement in micro-channels. Applied Thermal Engineering, 2017.

Al-Asadi, M.T., F.S. Alkasmoul, and M.C.T. Wilson, Heat transfer enhancement in a micro-channel cooling system using cylindrical vortex generators. International Communications in Heat and Mass Transfer, 2016. 74: p. 40-47.

Al-Asadi, M.T., Mohammed, H.A., Akhtar, S.N., Kherbeet, A.S. and Dawood, H.K., 2017. Heat transfer enhancements using traditional fluids and nanofluids in pipes with different orientations: a review. Journal of Nanofluids, 6(6), pp.987-1007.

Al-Asadi, M.T., Mohammed, H.A., Kherbeet, A.S. and Al-Aswadi, A.A., 2017. Numerical study of assisting and opposing mixed convective nanofluid flows in an inclined circular pipe. International Communications in Heat and Mass Transfer, 85, pp.81-91.

Albadr, J., S. Tayal, and M. Alasadi, Heat transfer through heat exchanger using Al2O3 nanofluid at different concentrations. Case Studies in Thermal Engineering, 2013. 1(1): p. 38-44.

Al-damook, A., Kapur, N., Summers, J., and Thompson, H. (2015). An experimental and computational investigation of thermal air flows through perforated pin heat sinks. Applied Thermal Engineering. 89, 365-376.

Al-damook, A., Kapur, N., Summers, J., and Thompson, H. (2016). Computational design and optimisation of pin fin heat sinks with rectangular perforations. Applied Thermal Engineering. 105, 691-703.

Al-damook, A., Summers, J., Kapur, N., and Thompson, H. (2016). Effect of Different Perforations Shapes on the Thermal Hydraulic Performance of Perforated Pinned Heat Sinks. International Journal of Multidisciplinary Engineering Science and Technology, 4 (3): 4475–4480.

Al-damook, A., Summers, J., Kapur, N., and Thompson, H. (2016). Effect of temperature-dependent air properties on the accuracy of numerical simulations of thermal airflows over pinned heat sinks. International Communications in Heat and Mass Transfer. 78, 163-167.

Al-damook, A. and Alkasmoul, F., 2018. Heat transfer and airflow characteristics enhancement of compact plate-pin fins heat sinks–a review. Propulsion and Power Research

Alkasmoul, Fahad Saleh (2015) Characterisation of the Properties and Performance of Nanofluid Coolants with Analysis of Their Feasibility for Datacentre Cooling. PhD thesis, University of Leeds

Almaneea, Abdulmajeed H (2014) Thermal analysis of liquid immersed electronics for data centres. PhD thesis, University of Leeds.

Al-Sallami, W., Al-Damook, A., and Thompson, H. (2016). A numerical investigation of thermal airflows over strip fin heat sinks. International Communications in Heat and Mass Transfer. 75, 183-191.

Al-Sallami, W., Al-Damook, A. and Thompson, H.M., 2016. A numerical investigation of thermal airflows over strip fin heat sinks. International Communications in Heat and Mass Transfer, 75, pp.183-191.

Alutronic.De (2015) http://www.alutronic.de/POWERBLOCS-Stiftkuehlkoerpe r-Aluminium-pur_detail_804.html

Amol B. D., Farkade H. S. (2013). Heat Transfer Analysis of Cylindrical Perforated Fins in Staggered Arrangement. International Journal of Innovative Technology and Exploring Engineering (IJITEE), 28, 621-632.

Anandan, S. and Ramalingam, V. (2008). Thermal management of electronics: A review of literature. Thermal Science, 12, 5-26.

Business Communications Company (BCC Research, 2011) http://www.bccresearch.com/market-research/semiconductor-manufacturing/thermal-management-technologies-market-smc024g.html.

Cengel, Yunus A., Cimbala John M. (2006) Fluid Mechanics, Fundamentals and Applications. McGraw-Hill.

Chi, Y.Q., Summers, J., Hopton, P., Deakin, K., Real, A., Kapur, N. and Thompson, H., 2014, March. Case study of a data centre using enclosed, immersed, direct liquid-cooled servers. In Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM), 2014 30th Annual (pp. 164-173). IEEE.

Dai, J., Ohadi, M. M., Das, D., and Pecht, M. (2014). Optimum cooling of data centers: application of risk assessment and mitigation techniques.

Dhanawade, K. H. and Dhanawade H. S. (2010). Enhancement of Forced Convection Heat Transfer from Fin Arrays with Circular Perforation. IEEE, Frontiers in Automobile and Mechanical Engineering (FAME), 192-196.

Dhanawade, K. H., Sunnapwar, V. K. and Dhanawade, H. S. (2014). Optimization of Design Parameters for Lateral Circular Perforated Fin Arrays under Forced Convection. Heat Transfer-Asian Research.

Dhanawade, K. H., Sunnapwar, V. K., and Dhanawade, H. S. (2014). Thermal Analysis of Square and Circular Perforated Fin Arrays by Forced Convection. International Journal of Current Engineering and Technology, 2, 109-114.

Diani, A., Mancin, S., Zilio, C. and Rossetto, L. (2013). An assessment on air forced convection on extended surfaces: Experimental results and numerical modeling. International Journal of Thermal Sciences, 67, 120-134.

Fahad S. Alkasmoul, T.G.M., M. C. T. Wilson, H. M. Thompson, M. T. Al-Asadi, A practical evaluation of the performance of Al2O3-water, TiO2-water and CuO-water nanofluids for convective cooling. International Journal of Heat and Mass Transfer, 2018.

Ganorkar, A.B. and Kriplani, V.M. (2012). Experimental Study of Heat Transfer Rate by Using Lateral Perforated Fins in a Rectangular Channel. MIT International Journal of Mechanical Engineering, 2, 91-96.

Greenberg, S., Mills, E., Tschudi, B., Rumsey, P. and Myatt, B. (2006). Best practices for data centres: Lessons learned from benchmarking 22 data centres. Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings in Asilomar, CA. ACEEE, August, 3, pp.76-87.

Gurrum, S. P., Suman, S. K., Joshi, Y. K., and Fedorov, A. G. (2004). Thermal issues in next-generation integrated circuits. Device and Materials Reliability, IEEE Transactions on, 4, 709-714.

Ismail M.F., Hasan M.N., and Ali M. (2014). Numerical simulation of turbulent heat transfer from perforated plate-fin heat sinks. Heat and Mass Transfer 50(4), pp.509-519.

Ismail, M. F., Hasan, M. N. and Ali, M. (2013a). Numerical simulation of turbulent heat transfer from perforated plate-fin heat sinks. Heat and Mass Transfer, 50, 509-519.

Ismail, M. F., Hasan, M. N. and Saha, S. C. (2014). Numerical study of turbulent fluid flow and heat transfer in lateral perforated extended surfaces. Energy, 64, 632-639.

Ismail, M. F., Reza, M. O., Zobaer, M. A. and Ali, M. (2013b). Numerical Investigation of Turbulent Heat Convection from Solid and Longitudinally Perforated Rectangular Fins. Procedia Engineering, 56, 497-502

Jeng, T. M., and Tzeng, S. C. (2007). Pressure drop and heat transfer of square pin-fin arrays in in-line and staggered arrangements. International Journal of Heat and Mass Transfer, 50, 2364-2375.

Jia, T. H., Kim, S. Y., and Chang, K. S. (2004). Cooling performance of triangular folded fin heat sinks in a duct flow. Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM'04. The Ninth Intersociety Conference, 325-330. IEEE.

Jia, T. H., Kim, S. Y., and Hyun, J. M. (2007). Pressure Drop and Heat Transfer Correlations for Triangular Folded Fin Heat Sinks. IEEE TRANSACTIONS ON COMPONENTS AND PACKAGING TECHNOLOGIES. 30, 3-8.

Jonsson, H., and Moshfegh, B. (2001). Modeling of the thermal and hydraulic performance of plate fin, strip fin, and pin fin heat sinks-influence of flow bypass. Components and Packaging Technologies, IEEE Transactions on, 24, 142-149.

Kherbeet, A.S., Mohammed, H.A., Ahmed, H.E., Salman, B.H., Alawi, O.A., Safaei, M.R. and Khazaal, M.T., 2016. Mixed convection nanofluid flow over microscale forward-facing step-Effect of inclination and step heights. International Communications in Heat and Mass Transfer, 78, pp.145-154.

Kherbeet, A.S., Mohammed, H.A., Ahmed, H.E., Salman, B.H., Alawi, O.A., Safaei, M.R. and Khazaal, M.T., 2016. Mixed convection nanofluid flow over microscale forward-facing step—Effect of inclination and step heights. International Communications in Heat and Mass Transfer, 78, pp.145-154.

Kherbeet, A.S., Safaei, M.R., Mohammed, H.A., Salman, B.H., Ahmed, H.E., Alawi, O.A. and Al-Asadi, M.T., 2016. Heat transfer and fluid flow over microscale backward and forward facing step: a review. International Communications in Heat and Mass Transfer, 76, pp.237-244.

Kherbeet, A.S., Safaei, M.R., Mohammed, H.A., Salman, B.H., Ahmed, H.E., Alawi, O.A. and Al-Asadi, M.T., 2016. Heat transfer and fluid flow over microscale backward and forward facing step: a review. International Communications in Heat and Mass Transfer, 76, pp.237-244.

Khoshnevis, A., Talati, F., Jalaal, M. and Esmaeilzadeh, E (2009a). Analysis of Heat-Transfer Enhancement and Design Parameters of Heat-Sink with Perforated Rectangular Ribs. International Journal of Scientific & Engineering Research, 4, 1-8.

Khoshnevis, A., Talati, F., Jalaal, M. and Esmaeilzadeh, E (2009b). Heat Transfer Enhancement of Slot and Hole Shape Perforations in Rectangular Ribs of a 3D Channel. 17th Annual (International) Conference on Mechanical Engineering, University of Tehran, 1-6.

Kim, D.K., Kim, S. J. and Bae, J.K. (2009). Comparison of thermal performances of plate-fin and pin-fin heat sinks subject to an impinging flow. International Journal of Heat and Mass Transfer, 52, 3510-3517.

Mcmillin, T. W. (2007). Thermal Management Solutions for Low Volume Complex Electronic Systems. M. Sc. Thesis, College Park, University of Maryland.

Mostafavi, G. (2012). Natural convective heat transfer from interrupted rectangular fins. Master of Applied Sciences: School of Engineering Science, Simon Fraser University.

Mostafavi, G. (2012). Natural convective heat transfer from interrupted rectangular fins. Master of Applied Sciences: School of Engineering Science, Simon Fraser University.

Naidu, M. S. and Kamaraju, V. (2013). High voltage engineering. New York, McGraw-Hill.

Naphon, P. and Khonseur, O. (2009). Study on the convective heat transfer and pressure drop in the micro-channel heat sink. International Communications in Heat and Mass Transfer, 36, 39-44.

Naphon, P. and Wongwises, S. (2010). Investigation on the jet liquid impingement heat transfer for the central processing unit of personal computers. International Communications in Heat and Mass Transfer, 37, 822-826.

Naphon, P., and Wongwises, S. (2011). Experimental Study of Jet Nanofluids Impingement System for Cooling Computer Processing Unit. Journal of Electronics Cooling and Thermal Control. 01, 38-44.

Naphon, P., Klangchart, S. and Wongwises, S. (2009). Numerical investigation on the heat transfer and flow in the mini-fin heat sink for CPU. International Communications in Heat and Mass Transfer, 36, 834-840.

Pan, Y., Yin, R., and Huang, Z. (2008). Energy modeling of two office buildings with data center for green building design. Energy & Buildings. 40, 1145-1152.

Prashanta Dutta, S. D. (1998). Effect of baffle size, perforation, and orientation on internal heat transfer enhancement. International Journal of Heat and Mass Transfer, 41, 3005-3013.

Sahin, B. and Demir, A. (2008a). Performance analysis of a heat exchanger having perforated square fins. Applied Thermal Engineering, 28, 621-632.

Sahin, B. and Demir, A. (2008a). Performance analysis of a heat exchanger having perforated square fins. Applied Thermal Engineering, 28, 621-632.

Sahin, B. and Demir, A. (2008b). Thermal performance analysis and optimum design parameters of heat exchanger having perforated pin fins. Energy Conversion and Management, 49, 1684-1695.

Sahin, B. and Demir, A. (2008b). Thermal performance analysis and optimum design parameters of heat exchanger having perforated pin fins. Energy Conversion and Management, 49, 1684-1695.

Sahin, B., Yakut, K., Kotcioglu, I. and Celik, C. (2005). Optimum design parameters of a heat exchanger. Applied Energy, 82, 90-106.

Sahin, B., Yakut, K., Kotcioglu, I. and Celik, C. (2005). Optimum design parameters of a heat exchanger. Applied Energy, 82, 90-106.

Sara, O. N, Pekdemir, S, S. Yapici and M. Yilmaz (2001). Heat Transfer Enhancement in a Channel Flow with Perforated Rectangular Blocks. International Journal of Heat and Fluid Flow, 22, 509-518.

Sara, O. N, Pekdemir, S, S. Yapici and M. Yilmaz (2001). Heat Transfer Enhancement in a Channel Flow with Perforated Rectangular Blocks. International Journal of Heat and Fluid Flow, 22, 509-518.

Sara, O. N, T. Pekdemir, S. Yapici and H. Ersahan (2000). Thermal Performance Analysis for Solid and Perforated Blocks Attached on a Flat Surface in Duct Flow. Energy Conversion & Management, 41, 1010-1028.

Sara, O. N., (2003). Performance analysis of rectangular ducts with staggered square pin fins. Energy Conversion and Management. 44, 1787-1803.

Shaeri, M. R. and Jen, T.C. (2012). The effects of perforation sizes on laminar heat transfer characteristics of an array of perforated fins. Energy Conversion and Management, 64, 328-334.

Shaeri, M. R. and YaghOUBI, M. (2009a). Numerical analysis of turbulent convection heat transfer from an array of perforated fins. International Journal of Heat and Fluid Flow, 30, 218-228.

Shaeri, M. R. and Yaghoubi, M. (2009b). Thermal enhancement from heat sinks by using perforated fins. Energy Conversion and Management, 50, 1264-1270.

Ismail M.F. (2013). Effects of perforations on the thermal and fluid dynamic performance of a heat exchanger. IEEE Transactions on Components, Packaging and Manufacturing Technology. 3, 1178-1185.

Shaeri, M. R., Yaghoubi, M. and Jafarpur, K. (2009). Heat transfer analysis of lateral perforated fin heat sinks. Applied Energy, 86, 2019-2029.

Shah, A., Patel, C., Bash, C., Sharma, R., and Shih, R. (2008). Impact of rack-level compaction on the data center cooling ensemble. In Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM. 11th Intersociety Conference on (pp. 1175-1182). IEEE.

Soodphakdee Denpong, M. B. A. D. W. C. (2001). A Comparison of Fin Geometries for Heat Sinks in Laminar Forced Convection Part I: Round Elliptic, and Plate Fins in Staggered and In-Line Configurations The International Journal of Microcircuits and Electronic Packaging, 24, 68-76.

Triplet (2012) Optimize Airflow Management in your Data Center. http://www.triplite.com/lp/direct/rackcooling/.

Tuma P.E. (2010). The merits of open bath immersion cooling of datacom equipment. Annual IEEE Semiconductor Thermal Measurement and Management Symposium. 123-131.

Villa, H. (2006), Rittal liquid cooling series, White paper 04. http://www.rittal.de/downloads/rimatrix5/cooling/WP%20Liquid%20Cooling_Stand%20Jan%202006_englisch.pdf.

Yaghoubi, M.A., Shaeri, M.R. and Jafarpur, K., 2009. Three-dimensional numerical laminar convection heat transfer around lateral perforated fins. Computational Thermal Sciences: An International Journal, 1(3).

YAKUT, K., ALEMDAROGLU, N., KOTCIOGLU, I. and CELIK, C. (2006a). Experimental investigation of thermal resistance of a heat sink with hexagonal fins. Applied Thermal Engineering, 26, 2262-2271.

Yakut, K., Alemdaroglu, N., Sahin, B. and Celik, C. (2006b). Optimum design-parameters of a heat exchanger having hexagonal fins. Applied Energy, 83, 82-98.

Yang, K. S., Chu, W. H., Chen, I. Y. and Wang, C. C. (2007). A comparative study of the airside performance of heat sinks having pin fin configurations. International Journal of Heat and Mass Transfer, 50, 4661-4667.

Yuan, W., Zhao, J., Tso, C. P., Wu, T., Liu, W. and Ming, T. (2012). Numerical simulation of the thermal hydraulic performance of a plate pin fin heat sink. Applied Thermal Engineering, 48, 81-88.

Zeadally, S., Khan, S. U., and Chilamkurti, N. (2012). Energy-efficient networking: past, present, and future. The Journal of Supercomputing: An International Journal of High-Performance Computer Design, Analysis, and Use. 62, 1093-1118.

Zhang, H. Y., Pinjala, D., Wong, T. N., Toh, K. C. and Joshi, Y. K. (2005). Single-phase liquid cooled microchannel heat sink for electronic packages. Applied Thermal Engineering, 25, 1472-1487.

Zhou F. and Catton, I. (2011). Numerical Evaluation of Flow and Heat Transfer in Plate-Pin Fin Heat Sinks with Various Pin Cross-Sections. Numerical Heat Transfer, Part A: Applications, 60, 107-128.