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ORIGINAL ARTICLE

Heat transfer and airflow characteristics enhancement of compact plate-pin fins heat sinks – a review

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Abstract Plate-pin heat sinks are widely used for the electronic cooling system, internal combustion IC engine, cooling of gas turbine blades and other different applications to enhance the thermal performance of heat sinks due to simplicity, low cost, and a reliable manufacturing process. However, compact heat sinks give higher pressure drop compared with other types of heat sinks. The purpose of this article is to summarise the main advantages and disadvantages of the compact heat sink with some recommendation studies for future works heat sink thermal airflow experiment and simulations. Furthermore, the research attempts to highlight the importance of balance the relationship between the hydraulic performance and the thermal performance of compact heat sinks.

1. Introduction

Since education, business, transportation, social media and the financial services have depended on information and communication technology (ICT). ICT has become the most important source of information and data in our society [1]. Thus, data centres, which are essentially digital factories, have become a vital part of ICT processing, management, storage and exchange of data [2]. 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 equipment (lighting and fire

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Nomenclature

A_c	cross-sectional area of the flow passage of the heat sink (unit: m^2)
D	pin diameter of the pin fin heat sink (unit: mm)
D	perforation diameter of the pin fin (unit: mm)
D_h	hydraulic diameter (unit: m)
H	pin fin height (unit: mm)
θ	Thermal resistance (unit: K/W)
h_p	Projected heat transfer coefficient
h	heat transfer coefficient (unit: $W/(m^2 \cdot K)$)
k	turbulence kinetic energy
n	number of perforations
N	number of pins
Ra	Rayleigh number
Re	Reynolds number
T	thermodynamic temperature (unit: K)
V	electric potential (unit: V)
w	electromagnetic energy density (unit: J/m^3)
Nu	Nusselt number
P	fan power (unit: W)
Δp	pressure drop (unit: Pa)
Pr	Prandtl number
Pr_t	turbulent Prandtl number
Q	power applied on the base (unit: W)
S_z	pin pitch in streamwise direction (unit: mm)

Greek letters

α	fluid thermal diffusivity (unit: m^2/s)
μ	fluid viscosity (unit: $Pa \cdot s$)
μ_t	turbulent eddy viscosity (unit: $Pa \cdot s$)
ρ	fluid density (unit: kg/m^3)
ν	kinematic viscosity (unit: m^2/s)
ν_t	turbulent kinematic viscosity (unit: m^2/s)
σ_ε	k-ε turbulence model constant
σ	turbulence model constant for the k-equation
ω	k-ω turbulence model constant

protection systems) [3]. Electronic component systems that arrange processing, storing and transmission of data is the main part of the data centre, according to Shah et al. [4] and Greenberg et al. [5], all of which and create a large amount of heat, which must be removed from the ICT components at a designed sufficient rate to avoid serious overheating problems and system failures [6]. More than nearly 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 central processing unit (CPU) [3].

The reliable performance of high power density electronics is important for the design of efficient cooling strategies. The thermal effects cause some of the failure mechanisms in electronic component devices, as 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 of these devices. For each 10 °C increase above the operating temperature (80–85 °C) of high power electronics, the rate of these failures almost doubles [6,7]. Thus, the crucial significance, as is reflected in the market, is electronics thermal management. Another important factor is the costs increase of thermal management products that are from nearly \$7.5 billion in 2010 to \$8 billion in 2011, and it is reached to \$10.9 billion in 2016, the annual rate of increase is 6.4%. Fans and heat sinks (HSs) as thermal management hardware take part for 84% of the total market. However, software, interface materials, and substrates as other main cooling product account between 4% and 6% of the market [8].

2. Heat sinks fabrication

Finned heat sinks have two main types: plate fins heat sink and pin fins heat sink that have been manufactured and produced by several big and small companies. For example, Airedale Company in the UK [9] and The Raypak company in the USA [10]. A set of base tube materials which have high thermal conductivity as copper, aluminium, brass, copper/nickel, aluminium/brass, could be used to manufacture finned heat sinks (FHSs) depending on the cost and the manufacturing simplicity of these materials. In recent years, the technology of finned heat sink design has reached the common techniques for electronics cooling.

One of the most recent vital methods in enhanced heat sink performance is pin fin technology. Because the pinned heat sink appropriates for many applications involving processes using gases or liquids. The main reason for that the characteristic of heat transfer in electronics cooling for pin fins HS technology is excellent [11–14]. Furthermore, to overcome the problems related to heat transfer enhancement as high pressure drop loss; low average heat transfer efficiency; and large thermal resistance, pin fins heat sink as extended surfaces could be utilised in electronic devices. Fins morphology has an important function in manufacturing and heat transfer characteristics. Cylindrical, rectangular and conical or semi conical are the widespread uniform geometry of pin fins. Therefore, it seems that it is a suitable time to employ this technology in traditional heat sinks in industrial applications as well.

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.

3. Industrial applications heat sinks

In many engineering applications, the power dissipation creates heat as a by-product and then the performance of engineering systems could be decreased by this undesirable heat. That because certain temperature limits are designed for almost all these applications to work within suitable conditions. The engineering devices might lead to a failure if surpassing these limitations by overheating. Currently, the sizes of electronic devices are decreasing at the same time the thermal power losses of these devices are increasing [15].

The industrial applications of the forced convection of heat sinks are various from the cooling of the electronic component to cooling of fuel element in nuclear reactors [16–18], and [19–21]. All sort of heat sinks based on the required type of applications. For example, if the pressure drop is not an important factor, fin-foam or Schwartz type structure could be very recommended. However, if the pressure drop is a concern as more than 20 Pa [20], it could be suitable to utilise parallel plate fins. While honeycomb heat sinks are used for the applications that have a pressure drop less than 20 Pa [20]. Moreover, if the pumping power is specified, honeycomb, fin-foam, and Schwartz type structure can be improved the thermal performance [20]. As the ratio of height to diameter of pin fins (H/d) is between 0.5 and 4 these fins called short fins which are used on the trailing edges of the gas turbine, electronic cooling, and aerospace industry. This ratio, however, when exceed 4 pin fins are long and they are used in the heat exchanger applications [16,22].

Plate and pin fins are used for cooling of CPU of a personal computer, electronic component devices [23–34] integrated circuit chips in electronic equipment, compact heat exchanger, and cooling of advanced gas turbine blades [35–37].

4. Plate-pin heat sinks (SPPHSs) or compound heat sinks (CHSs)

Plate-pin fin heat sinks are kind of compact heat sinks (CHSs), as shown in Figure 1 and have been reported on only in relation to turbulent airflow. Compact heat sinks (CHSs) consist of some pins as turbulators among plate fins in in-line and staggered arrangements. As more pins are present among the plate fins, the boundary layer growth through the heat sink is inhibited because the pins act as obstructions. The benefits of compact heat sinks are a reduction of the CPU temperature and thermal resistance and enhancement of the Nusselt number, compared with plate fins and pin HSs. However, these pins will impede airflow, which leads to a pressure drop, and fan power for compact heat sinks is huge in comparison with other plate fins and pin HSs.

This section presents some relevant and representative studies conducted with regard to cool electronic components using compound heat sinks (PCPFHS and PSPFHS) with air and liquid coolant.

Generally, electronic systems in data centres are cooled by liquid or air [38]. Liquid cooling such as water, nanofluids, polymers, and dielectric liquid (Hydrofluoroethers, HFE) can be used to cool the heat sinks and

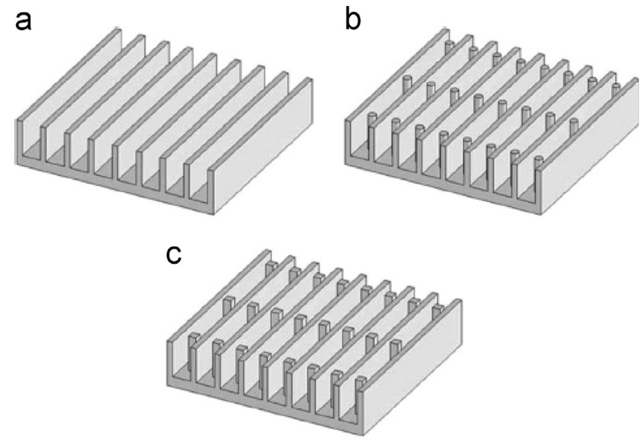

Figure 1 Compact heat sinks: (a) plate-fin heat sink, (b) plate-circular pin-fin heat sink, and (c) plate-square pin-fin heat sink [47].

servers of racks in data centres and other different applications. Direct contact liquid cooling techniques, such as immersing servers into dielectric liquid may be used [39,40]. Ramifications of immersion on data centre cooling and energy performance can be found in Chi et al. [41]. 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 [42]. 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 [43,44]. However, the main disadvantages of the pressure drop and pumping power of liquids are higher compared with that of air because the viscosity and density of liquids are larger than those of air cooling technique. Furthermore, liquid cooling is a risk of the liquid leaking, which may damage the server's electronic components, resulting in data centre loss. It could avoid this problem by applying vacuum pressure through a system. It means pulling liquid through cooling liquid system instead of pushing it. The risk of condensation forming, which may lead to a failure in the system, that solved by increasing inlet liquid temperature [42,43]. The high cost of maintenance and installation; and an increase in infrastructures such as pipe work, leak detection, and installation of insulation. Thus, it is required optimum study to evaluate those problems compared with heat transfer enhancement and air cooling technique [44].

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

Table 1 Pin dimensions types of the heat sinks [46].

Type	The height of pin fins/mm		
	Pin-1	Pin-2	Pin-3
Type-1	5	5	5
Type-2	5	5	10
Type-3	5	10	10
Type-4	10	10	10

$L = 51$ mm, $H = 10$ mm, $N = 9$, $t = 1.5$ mm, and $D = 2$ mm.

heat exchanger, which is a vital practice employed in air-cooling systems. This transfer mechanism is easy, simple and leads to reduced cost [45]. However, the heat transfer rate of the air-cooling method is lower than that of the liquid cooling, as indicated previously.

In this technique, the heat transfer rate of the heat sink can be augmented, either by increasing the fan speed or the surface temperature of the heat sink. As the fan speed increases, however, the fan's reliability reduces and it consumes a lot more power 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 [45]. Hence, increasing fan speed and increasing the temperature are not a favoured approach.

Therefore, these challenges need to be addressed by inventing an effective air cooling solution that has direct influences on the reliability, power, and performance of electronic devices.

4.1. Air cooling

Yang and Peng [37,46] investigated two papers related to the compact heat sink. Thermal performance and pressure drop of plate circular pin fins heat sink (PCPFHS) which consists of some circular pin fins between those plate fins in in-line and staggered arrangement as the first investigation [37]. The range of velocity was 6.5, 8, 10 and 12.2 m/s and the length, height and thickness of this plate fin are 51, 10 and 1.5 mm, respectively. In addition, the number and diameter of fins are 9 fins, 2 mm, respectively with mixed-height design on PPFHS is shown in Table 1. The results indicate that the thermal resistance of (PCPFHS) is smaller than that of the pin fins heat sink (PFHS). However, the pressure drop of (PCPFHS) is higher than that of the (PFHS). The synthetic performance of (PCPFHS) outperforms on the (PFHS) and the best one is type-3. Moreover, for in-line arrays design, the synthetical performance is better than staggered arrays model. The second report [46] deals with the effects of shape and arrangement of pin fins on the thermal and hydraulic performance of compound heat sinks utilising circular and square pin fins between plate fins are addressed. Governing equations are solved via employing a finite difference scheme. These compound heat

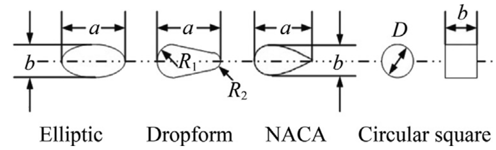

Figure 2 Different types of pins cross-sections [49].

sinks are called plate-circular pin fins heat sink (PCPFHS) and plate-square pin fins heat sink (PSPFHS), as shown in Figure 1. The boundary conditions and the dimensions of both heat sink and fins are similar to the paper [46]. The findings show that arrangements of fins do not have any influence on the thermal and hydraulic performance of compound heat sinks. Furthermore, the thermal resistance of the compound heat sinks is smaller than that of plate fins heat sink (PFHS) whereas, the pressure drop of the compound heat sinks is highest. Moreover, the synthetic performance of (PCPFHS) outperforms on the (PSPFHS).

Kumar and Bartaria [47] assessed thermal performance and pressure drop of plate-elliptical pin fins heat sink (PEPFHS) which consists of some elliptical pins between those plate fins in-line arrangement. The range of parameters is regarded as air velocity is 6.5, 9.5 and 12.5 m/s; the length, height, thickness of this plate fin heat sink, and fin-to-fin distance are 51, 10, 1.5, and 5 mm, respectively; heating power is constant at 10 W in all cases. In addition, the number of elliptical pins is 9 pin fins, major and three different minor radiuses of elliptical pins are 5 mm, and 1.5, 2, 2.5 mm, respectively. In order to solve the governing equations, the k-ε turbulent model is used by utilising FLUENT 12.1 programme based on the finite volume method. The results indicate that thermal resistance and the Nusselt number of (PEPFHS) enhance with decreasing the minor radiuses of elliptical pins. Furthermore, the Nusselt number of (PEPFHS) is higher than that of the plate pin (PFHS). However, the pressure drop of (PFHS) is lower than that of the (PEPFHS).

With more different plate-pin fin heat sinks models with various: cross sections types of pin-fin (square, circular, elliptic, NACA 0050 profile, and dropform), as shown in Figure 2; and the ratio of pin width to plate fin spacing from 0.3 to 0.6 with increment value 0.1 have reported by Zhou and Catton [48] to enhance thermal and hydraulic performance of this kind of heat sinks. The number of those plate-pin fin heat sinks (PPFHS) was 20 models. In addition, the range of parameters is considered in this study: length of the plate fin 51 mm, height of the base 3 mm, plate fin spacing 5 mm, transverse pitch of pin fins 6.5 mm, height of the fin 10 mm, plate fin thickness 1.5 mm, plate fin pitch 6.5 mm, longitudinal pitch of pin fins 6.5 mm, pin diameter of pin fin 1.5 mm, pin diameter of PPFHS 1.5, 2, 2.5 and 3 mm, and the air velocity is from 6.5 m/s to 12.2 m/s. The numerical data, which are obtained from the k-ω turbulent model by using ANSYS CFX-12.1 programme, illustrate that PPFHSs improve the Nusselt number, while pressure drop increases by comparison with plate fin (PFHS) and pinned

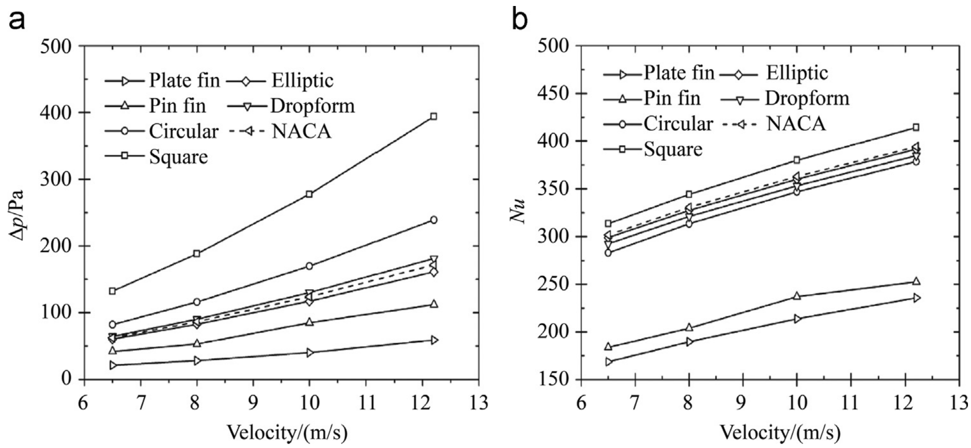

Figure 3 (a) Pressure drop and (b) Nusselt numbers of compact heat sinks [49].

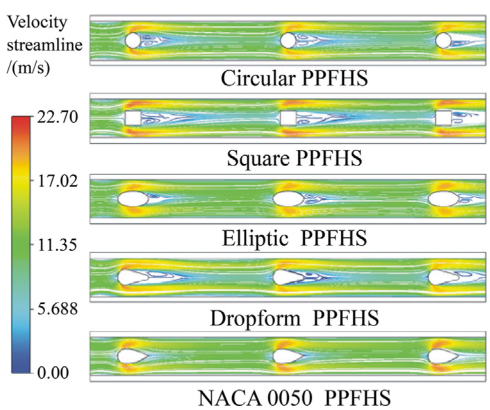

Figure 4 Streamline patterns at $U_c = 10$ m/s, in the plane $z = 8$ mm [49].

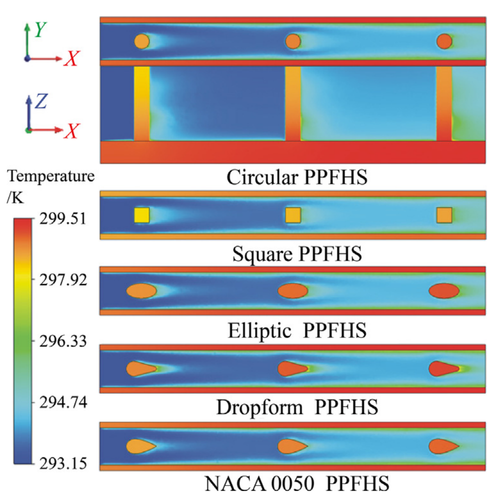

Figure 5 Temperature contour at $U_c = 10$ m/s, in the plane $z = 8$ mm [49].

heat sink (PHS), see Figure 3. However, some of the PPFHSs have better power consumption and heat transfer enhancement compared with a plate fin heat sink (PFHS). As shown in Figures 4 and 5, it is recommended to investigate of unsteady flow effects (e.g. vortex shedding) could be proposed as a future consideration.

Table 2 Different pin diameter combinations for four types of PPFHSs [50].

Type	The diameter of pin fins/mm		
	Pin-1	Pin-2	Pin-3
Type-1	1	1	1
Type-2	1	1	2
Type-3	1	2	2
Type-4	2	2	2

Four types of PPFHS.

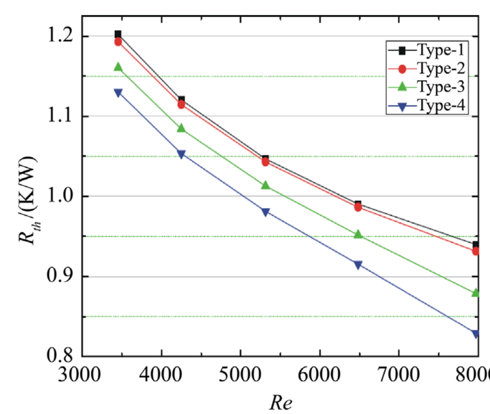

Figure 6 The influence of air velocity on thermal resistance with different pin diameter [50].

Yuan et al. [49] investigated the thermal hydraulic performance of compact plate pin fins heat sink in in-line and staggered arrangement and to find the potential application to the CPU of PC. Air velocity range was from 6.5 m/s to 15 m/s and the neighbour pins flow-directional centre distances (NPFDCD) of 4*D*, 6*D*, 8*D*, 10*D* and 12*D* are adopted. Heat sink dimensions and the boundary conditions are similar to the previous papers [46–48] with mixed pin diameter design on.

PPFHS is shown in Table 2. The results show that thermal hydraulic performance has affected by air velocity and pin diameter while the effect of (NPFDCD) and pin array of this compact HS was less remarkable. Pressure drop over PPFHSs

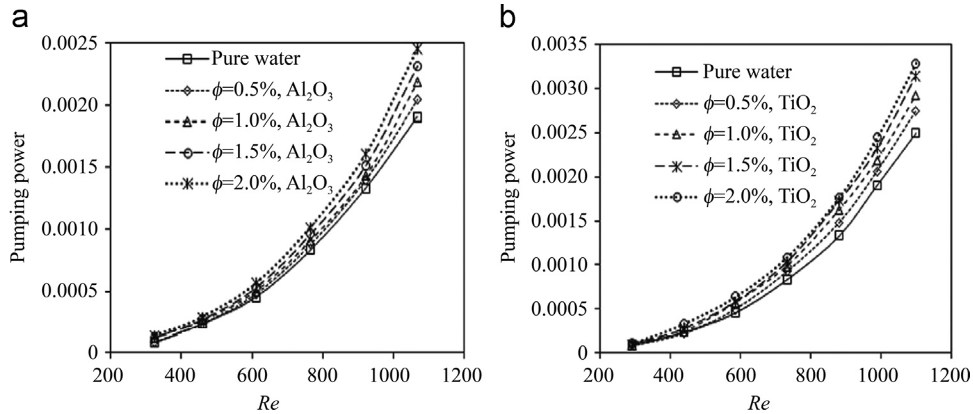

Figure 7 The influence of volume fraction and Reynolds number on pumping power of (a) Al_2O_3-water nanofluids and (b) TiO_2-water nanofluids [54].

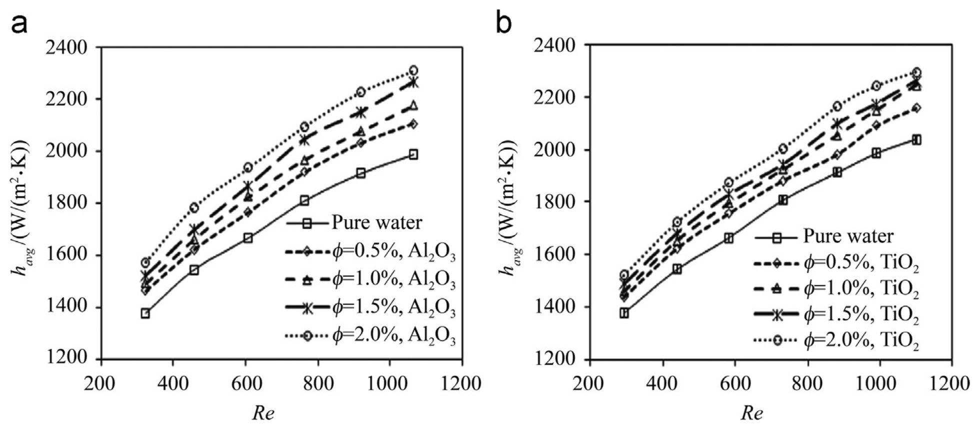

Figure 8 The influence of volume fraction and Reynolds number on average convective heat transfer coefficient of (a) Al_2O_3-water nanofluids and (b) TiO_2-water nanofluids [54].

(flow resistance) increases but the thermal resistance, Figure 6, and the profit factor will significantly decrease as the air velocity and pin diameter increase. The proposed all these models of PPFHS achieve the cooling requirement of a desktop PC CPU at less than 60 W as a heating power and maximum temperature of 85 ℃.

Yu et al. [50–52] numerical and experimental investigated the thermal and flow performance of plate-circular pin fins heat sinks (PCPFHSs) which consist of some circular pin fins between those plate fins in-line and staggered arrangement. The range of velocity was from 1–12 m/s as a laminar and turbulent flow. Length, height and thickness of this plate fin heat sink are 51, 10 and 1.5 mm, respectively. The *k-ε* turbulent model is used to solve the governing equations. The results indicate that the thermal resistance of (PCPFHS) is nearly 30% smaller than that of pinned heat sink (PFHS). However, the pressure drop of (PCPFHS) is higher than that of the (PFHS). The synthetic performance profit factor of (PCPFHS) is about 20% higher than that of (PFHS).

4.2. Liquid cooling

Relatively few studies have considered the effect of liquid cooling of compact heat sinks on the heat transfer and pressure drop, which is investigated experimentally in the following literature survey, rather than through numerical reports. It is indicated that liquid cooling of compact heat sinks offers considerable benefits by enabling the heat transfer to be improved while at the same time increasing both the pressure drop across the heat sink and the pumping power required to pump the liquid through it. The Al_2O_3-water nanofluids by Zirakzadeh, et al. [53] while the TiO_2-water and Al_2O_3-water nanofluids by Roshani, et al. [54] are investigated experimentally to explain the benefits of cooling nanofluids laminar flow with this kind of heat sinks. The expected finding may enhance the heat transfer rate while increasing the pumping power consumption, which is required to overcome the pressure drop across the heat sink. The minimization of CPU temperature and thermal resistance are the other important factor for thermal management of systems containing electronic components, together with minimising the fan power consumption. Zirakzadeh, et al. [53] experimental results showed that dispersion of Al_2O_3-water increased significantly the overall heat transfer coefficient, while the thermal resistance of heat sink decreased. In addition, the plate pin-finned heat sink showed an increase in the heat transfer coefficient up to 20% in comparison with the conventional plate fin heat sink. However, they did not explain the effect of pressure drop and pumping power through compact heat sinks. On the other hand, Roshani, et al. [54] have been shown the pumping power and heat transfer rate of compact heat sinks.

Although the experimental measurements showed that the pumping power for the volume concentration of 2% of TiO_2-water and Al_2O_3-water nanofluids increase 30% and 15%, respectively see Figure 7, the average heat transfer coefficients enhanced by 14% and 16%. The thermal resistance reduced by 14% and 17% for TiO_2-water and Al_2O_3-water nanofluid respectively, as shown in Figure 8.

Based on the previous literature review that the thermal performance is enhanced by plate-pin heat sinks while at the same time the fan or pumping power of compact heat sinks increase. Thus, one attempt to reduce fan power is using a splitter plate pin-fin heat sink (SPPFHS) as a new kind of heat sink in addition to enhancing the thermal performance of heat sinks [55]. This splitter is a thin plate is located behind the pin-fin, as shown in Figure 9. According to the numerical results [55], reduces the thermal resistance and pressure drop through the heat sink. Splitter streamlines the airflow around the pins and decreases the pressure drop across compact heat sinks.

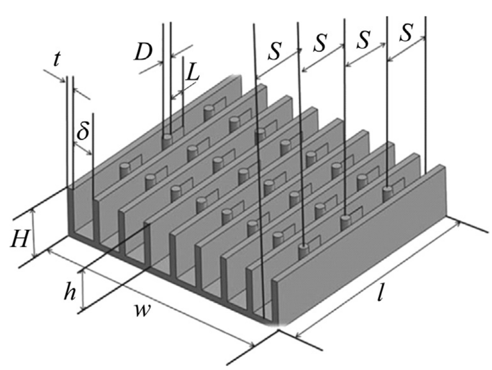

Figure 9 Schematic diagrams of splitter plate pin-fin heat sink (SPPFHS) [56].

Comparison between SPPFHS and plate-pin heat sink (PPFHS) confirms the ability of splitters in the modification of the hydro-thermal behaviour of heat sinks by simultaneous reducing the pressure drop and thermal resistance, as shown in Figure 10.

5. Future works

Many studies have been reported for almost fin heat sinks, however, according to author's knowledge it needs study numerically and experimentally for the following suggested points:

- For numerical studies, based on Al-damook, et al. [56,57], it is recommended that the variable air properties should be accounted for in future heat sink thermal airflow simulations it.
- Forced and natural convection laminar fluid flow study using compact plate-pin heat sinks liquid cooling.
- Turbulators could be in the form of winglets, rings, twisted rings, *Z*-shaped baffles vortex generator, obstacles, splitter pin-fin and perforated fins [58–60] that are used in compact heat sinks.
- Optimisation study of the cost of pumping power and heat transfer enhancement of compact heat sinks with using liquid cooling technique compared with conventional cooling technique (air cooling).
- The investigation of unsteady flow effects (e.g. vortex shedding) could be proposed as a future consideration [61].
- Investigate the effect of noise and vibration of the high level of inlet fluid on thermal and hydraulic characteristics of compact heat sinks [61].
- Using compact heat sinks in the solar air and water collectors and PV panels may increase the thermal performance with critical thinking about the pressure drop and fan or pumping power [61].

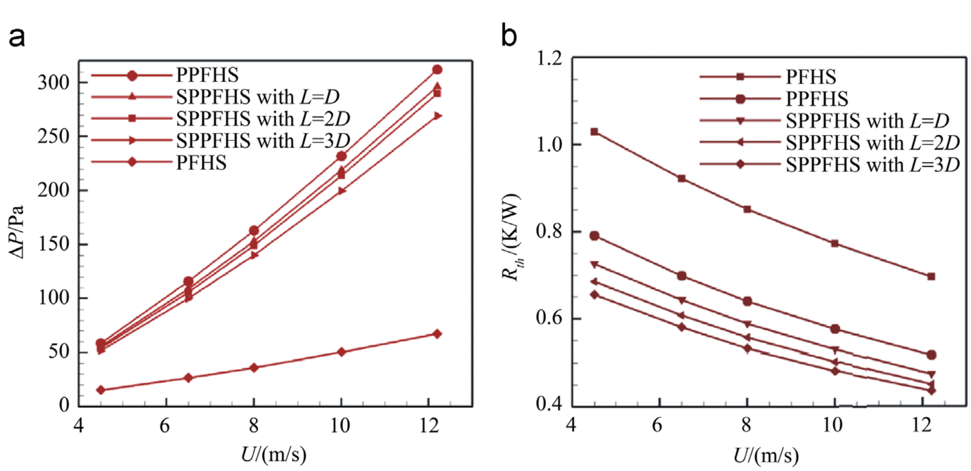

Figure 10 (a) Comparison of pressure drop and (b) thermal resistance for SPPFHS, plate-pin HSs, and plate fins HSs [56].

6. Main conclusions

An attempt has been made to review the thermal and hydraulic characteristics of plate-pin heat sinks (compact heat sinks) provided with pins as turbulators. These turbulators in the form of circular, square, elliptic pins are used in between plate fin heat sinks. Based on the literature it is found that the compact heat sinks are useful for reducing the CPU temperature and thermal resistance and enhancement of the Nusselt number, compared with plate fins and pin HSs. However, these pins will hinder airflow, which leads to a pressure drop, and fan power for compact heat sinks is huge in comparison with other plate fins and pinned HSs. Therefore, the need of developing vortex generators design focused on reducing the pressure drop penalty through heat sinks associated with this kind of cooling systems.

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