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Theoretical Investigation of a Pin Fin Heat Sink Performance for Electronic Cooling using Different Alloys Materials

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Theoretical Investigation of a Pin Fin Heat Sink Performance for Electronic Cooling using Different Alloys Materials

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Abstract. Electronic cooling plays a role in removing the electronic equipment's heat rate to prevent failure from occurring. Electronic cooling performance is based on many parameters, such as thermal characteristics and material type design. Pure aluminium, copper – aluminium, and aluminium - beryllium are selected for predicting the performance of a heat sink. It was observed that the presence of Aluminium -copper alloy raises the performance of the heat sink compared with that of the pure aluminium. In contrast, the heat sink performance using aluminium - beryllium alloy was less than that of the reference material (pure aluminium). It was found that the heat dissipated from the heat sink increases by 1.4 % with using aluminium -copper alloy instead of using pure aluminium while the heat dissipated drops by 2% with using aluminium - beryllium alloy compared with that of using pure aluminium. Further, the heat sink mass decreases with the use of the aluminium- beryllium and increases with using copper – aluminium instead of pure aluminium. Whereas the mass of the heat sink using aluminium -copper alloy is higher than that of the pure aluminium by 2.3% while the mass of the heat sink using aluminium - beryllium alloy is less than that of the pure aluminium by 2.4%.
Keywords. Heat sink, Passive cooling system, Composite materials, Fin efficiency.

1. Introduction

Electronic devices have been spread over the world cause an increase in the heat generation that should be released to keep the resources temperatures under control. Heat sinks are the most devices that use for such purposes [1] and [2]. Heat is dissipated from the heat sources through the heat sinks by the heat transfer process. Many types of heat sinks can be used to control the sources' temperatures based on their forms. Pin fin heat sink is one of them [3][4]. Also, in the manufacturing of the heat sinks, their materials have an essential effect on their performance. The thermal dissipation is not the only challenge of heat sink design because researchers should balance the thermal dissipation and pressure over the heat sink design [1]. Pin fin heat sink is the one that has been studied by many researchers [3] Khan et al. [5], [6] and [7], Chen et al. [4], and Yang et al. [8], which their studies indicated that the performance of pin-fin heat sink depending on the many factors. These factors include the pin heat sink materials, pin diameters, pin high, the distance between the pin-fins, density of pin, the type of interface material, geometry of heat sink, manufacturing methods, and velocity of the fluid through the heat sink. Afterward, Khan et al. [9] and Kang et al. [10] also introduced a study on the cylindrical fin heat sinks used in electronic cooling under the forced convention. They also assessed these parameters that affect the performance of a cylindrical fin heat sink. The efficiency and design optimization of the heat sink is presented by Azar et al. [11], who reported contour graphs which indicate the performance of air through a narrow channel of the heat sink in terms of factors of the performance such as fin thickness and the distance between channels of the sink. Also, Kondo et al. [12] presented a study to optimize pin-fin heat sinks for electronic cooling. They considered many factors that involve the distance between pins, pin diameter, and fin height. Moreover, heat transfer and pressure drop in micro Pin-fin heat sink were investigated experimentally by Abel Siu-Ho and Frank Pfefferkorn [13]. Thamer et al. [14] conducted an analytical investigation for longitudinal fins' best design on the panel radiator thermal performance. In July 2016, Raaid et al. introduced a study for the LED light's behavior based on the design required heat sink used for cooling. They used ANSYS software to carry out the heat sink model after design it using the EES program [15]. Afterward, Salem et al. investigated the effect of the reinforced carbon fiber on the heat sink performance. They examined different percentage of reinforce carbon fibre that are used with various values of applied energy. The study concluded that adding reinforced carbon fibre to the epoxy enhances the heat sink performance [16]. Jassem and Salem investigated the influential parameters on a cold plat that uses under the same technique of the heat sink. Their work was experimentally and numerically carried out using Star CCM+. They found that the affective factors that can improve the heat dissipation process [17]. Mohiuddin et al. studied design of the heat sink using aluminium material. Simulation and experimental investigations were applied on two designs of heat sinks. They concluded that the rectangular fin achieved results better than circular tube fin [18]. In 2019, a comparison investigation between spherical dimple and inclined teardrop dimple heat sinks were carried out by Perwez and Kumer [19]. They applied different flow rates to study the Nusselt number and pressure drop. ANSYS Fluent was utilized in their study. They concluded that the inclined teardrop heat sink is best in terms of heat transfer. At the same time, Moradikazerouni et al. investigated analytically three dimensions of a flat plate heat sink in forced convection. After they validated the work, it was found that enhancing the airflow leads to improving the heat sink [20]. In 2020, Tariq et al. investigated a mini channel heat sink. A slab in mini-channel was introduced, and its effects were evaluated. The slab's effects on the thermal performance of the heat sink were compared with and without a slab. They found that the slab reduced the base junction temperature by around 16% [21].

In 2018, an experimental article was presented by Hussein and Makhoul [22] that investigated the effect of fins material type in addition to the effect of perforations in both fins. The results revealed that the copper heat sink performance is better than the aluminium one. Also, the perforations enhance heat dissipation. In 2019 Rehman and Ali studied the aluminum heat sink thermal performance. They illustrated the effect of Copper and Nickel Foams on its performance. They found that Coper foam achieved better results than others [23]. In the same year, Dhaiban and Hussein abstracted previous studies investigating the enhancements of heat sink performance.

Moreover, they summarized the various enhancement techniques applied to optimize the hydrothermal design of different heat sinks types. Based on the reference, aluminum and Copper are the primary materials used to manufacture the heat sinks [24]. Mjallal et al. [25] have used different types of phases in examining the performance of the heat sink. Rohani et al. [26] studied the heat sink's performance using modified polymeric instead of aluminum as an alternative material. They found that there is an enhancement in the heat dissipated and thermal conductivity with using these materials. Deng et al. [27] investigated the heat sink's performance using phase change material. They have shown that the thermal enhancement of phase change material based heat sinks based on the phase change material volumetric fraction. Referring to the literature review and the best of the authors' knowledge, an increase in the heat dissipated from electronic cooling has been introduced by many parameters. The cost and high thermal conductivity of material are considered the most influential parameters that limit the heat sink design. Pure copper, pure aluminum, carbon foam, copper graphite-epoxy are the most available current materials that have been selected for a heat sink. Aluminum, copper, and zinc are among the better materials with good thermal conductivity and low cost. Aluminum is the most used material in heat sink fabrication since its light and has good thermal conductivity. Thus, it is essential to examine the material's thermal conductivity and its weight in any design selecting of the heat sinks. Alloys that are produce by combining different materials can be used in the design of the heat sink, as well. After choosing the suitable material, the design steps should be started that related to their performance. Since copper has high thermal conductivity but is slightly heavy, it can be combined with aluminum material to obtain acceptable weight and good thermal conductivity. Moreover, some materials have lightweight and acceptable thermal conductivity. Despite the continued studies of the material type effects on the heat sink performance, there are still many vital types of alloys that have not been studied extensively yet. Therefore, in this work, aluminum- copper and aluminum - Beryllium alloys material was selected to study the pin fin heat sink's thermal performance. Also, the influential thermal parameters of the pin heat sink's performance will be carefully considered for the design of the sinks using these alloy types. As a result, this work aims to introduce an investigation for the best design of the pin fin heat sink for the chip processor of electronic cooling devices using different aluminium- copper, aluminium- beryllium, and pure aluminium. However, the structure of this paper involves the mathematical model, results, and discussion.

2. Mathematical model

In this study, pin fin heat sinks' thermal performance is investigated analytically and numerically using the different materials. Aluminum- copper, pure aluminum, and aluminum - beryllium alloys material were used in this work. Table 1 indicates the properties of aluminum, copper, and beryllium.

Table 1. The properties of the utilizing materials.

Properties	Aluminum	AL_Copper	AL_Be
Thermal Conductivity (W/(m·K))	237	269	207
Density (g/cm3)	2.69	3.95	2.52

For this purpose, the geometry of the pin-fin heat sink is firstly defined and identified. The bottom heat sink is subjected to heat generation from an electronic source and is identified by the base and diameter of pins and their numbers. Therefore, the mathematical model has included pin fin heat sink modeling used to cool the electronic devices. The air properties are evaluated at the ambient temperature. The scheme of the pin fin heat sink is shown in Figure (1). Moreover, the pin fin heat sink design depends on the main parameters, including a source of power, junction temperature (less than 100 °C), heat transfer rate, and the pin fin heat sink's thermal resistance. The mean temperature of the heat source is t junction temperature T_S.

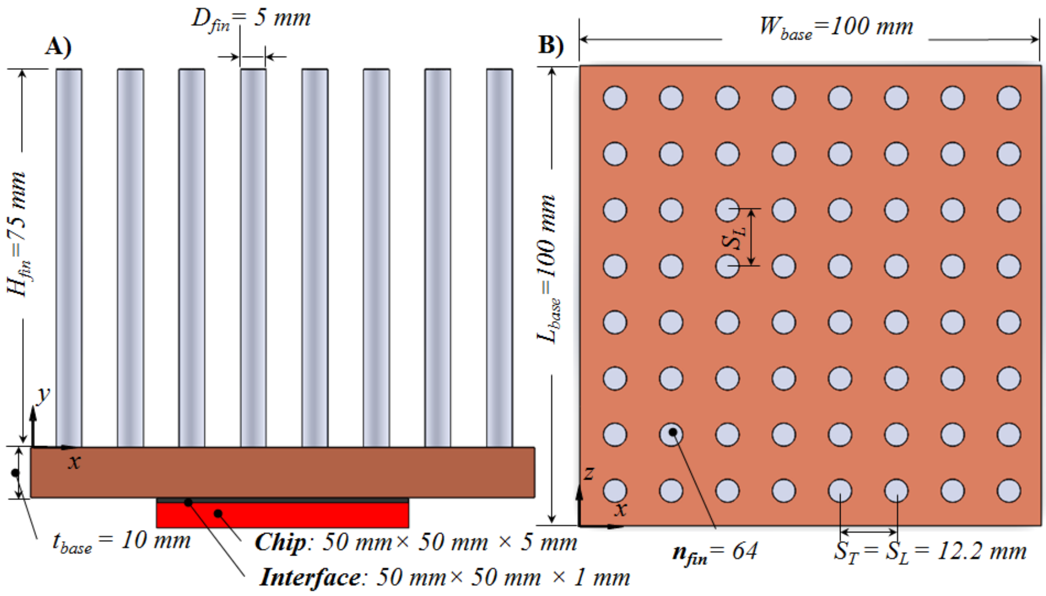

Figure 1. The scheme of the pin fin heat sink: A) front view, B) top view.

The pin fin heat sink's performance (n) is calculated based on many characterizes such as the mass of heat sink, overall heat transfer, heat transfer coefficient, the thermal resistance of pin fin heat sink, and corresponding Nusselt number [28]. The main characters in calculating the heat sink performance are thermal resistance, which must first be calculated [9] and [10]. In other words, the total thermal resistance of the pin-fin heat sink can be defined as the sum of all resistances, which involve interfacing thermal resistance and pin fin heat sink thermal (base thermal resistance conduction, radiation, and convection). Figure 2 shows the resistance analysis of the system.

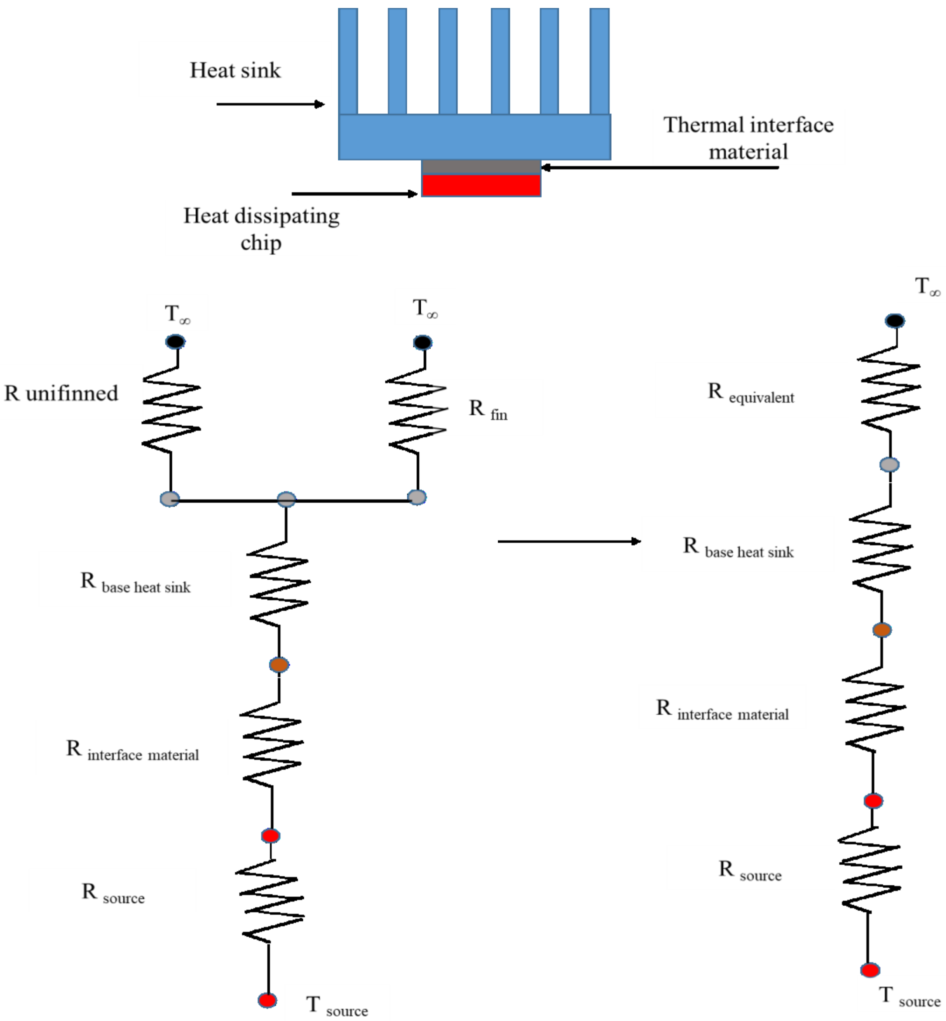

Figure 2. The resistance analyses of the system.

Therefore, the total heat transfer rate can be calculated based on the sum of all resistances, and the temperature difference as follows [12] [8][28]:

$$q_{total} = \frac{T_S - T_\infty}{R_{total}} \tag{1}$$

Due to the irregularities in the interface's surface between the pin fin heat sink base and the chip heat source, a temperature drop occurs over the interface between them. Thermal interface resistance is based on many parameters such as the thickness of the interface, the roughness of the surface, and the thermal conductivity of the contacting materials, including layers, coatings, and films, etc. Therefore, the interface resistance calculation can be written as [28] -

$$R_{interface} = \frac{t_{interface}}{A_{interface} * K_{interface}} \tag{2}$$

While the base thermal resistance depends on thermal conductivity thickness and the area of the base heat sink, which can be calculated as [28]:

$$R_{base} = \frac{t_{base}}{A_{base} * K_{base}} \tag{3}$$

The source (chip) resistance can be estimated as follows [28]:

$$R_{chip} = \frac{t_{chip}}{A_{chip} * K_{chip}} \tag{4}$$

The primary quantity in the overall thermal resistance is the thermal resistance of the pin fin heat sink, which is based on the fin efficiency, the surface area of the fin is A_{fin}, and the convection heat transfer coefficient is h_{fin}. Conduction and convection heat transfer is taken into consideration when analyzing the thermal contact resistance of the fin. Heat typically transfers through the pin fin heat sink by conduction and dissipated to the surrounding ambient air by convection. The fined resistance of the heat sink can be written as:

$$R_{fin} = \frac{1}{h_{fin} * \eta_{fin} * A_{fin}} \tag{5}$$

Heat is also transferred from the exposed (unfinned) surface of the baseplate, which can be written as:

$$R_{unfinned} = \frac{1}{(h_{unfinned} * A_{channel})} \tag{6}$$

where the heat transfer coefficient for the surface of the base plate and pin fin heat sink is developed by Khan et al. [9] as follows:

$$h_{unfinned} = \frac{0.75 K_f}{D_{fin}} \sqrt{\frac{S_T - 1}{n_{fin,L} S_L S_T}} Re_D^{0.5} * Pr_D^{0.3} \tag{7}$$

$$h_{fin} = \frac{C_1 K_f}{D_{fin}} Re_D^{0.5} * Pr_D^{0.3} \tag{8}$$

According to Khan [29], the constant C1 in Equation (8) is calculated depending on the following [9]:

$$C_1 = \left[0.2 + e^{(-0.55 S_L)}\right] {S_T}^{0.285} \; {S_L}^{0.212} \tag{9}$$

The Prandtl number is

$$Pr_{air} = \frac{\mu * c_p}{K} \tag{10}$$

The mean velocity in the minimum free cross-section between two rows, Umax, is used as a reference velocity in the calculations of fluid flow and heat transfer for both types of arrangements and is given by [29]:

$$U_{max} = max\left\{\frac{S_T}{S_T - 1} U_a, \frac{S_T}{S_L - 1} U_a\right\} \tag{11}$$

Ua is the approach velocity, SL, and ST are the dimensionless longitudinal and transverse pitches, and is the dimensionless diagonal pitch in a staggered arrangement. By combining Equations (6), (7), and (9) can be solved for the average heat transfer coefficient of the heat sink [5][3]:

$$h_{unfinned} = C_2 \frac{K_f}{D_{fin}} Re_D^{0.5} * Pr_D^{1/3} \tag{12}$$

Where C_2 is a constant and for both pin-fin arrangements, it is written as [5]:

$$C_2 = \frac{C_1 \pi \gamma \eta_{fin} + 0.75 \sqrt{\frac{S_T - 1}{n_{fin,L} S_L S_T}} \left(S_T S_L - \frac{1}{4}\right)}{\pi\left(\gamma - \frac{1}{4}\right) + S_T S_L} \tag{13}$$

and $\gamma = \frac{H}{D}$ is the aspect ratio of the fin. Thus, the dimensionless heat transfer coefficient for the heat sink may be expressed as [3][5][12]:

$$Nu = \frac{h_{air,base} * L_{base}}{k_{air}} \tag{14}$$

$$Nu = \frac{h_{fin} * D_{fin}}{k_{air}} \tag{15}$$

The efficiency of the fin with a constant heat transfer coefficient and an insulated tip is given by [12][5]

$$\eta_{\mathrm{fin}} = \frac{\tanh(mH)}{\mathrm{mH}} \tag{16}$$

Where $\mathrm{m} = \sqrt{\frac{4h_{fin}}{KD_{fin}}}$ with the fin parameter, Therefore, the overall thermal resistance of the heat sink can be determined from Equations (5) and (6) as follows:

$$\mathrm{R_{HS}} = \frac{1}{\frac{1}{\mathrm{R_{fin}}} + \frac{1}{\mathrm{R_{channel}}}} \tag{17}$$

Depending on previous equations of the resistance, the total resistance can be written as:

$$\mathrm{R_t} = \mathrm{R_{interface}} + \mathrm{R}_{base} + \mathrm{R}_{HS} + R_{source} \tag{18}$$

The mass of the heat sink was obtained as follows: $m = \rho * V$
After determining the value of total thermal resistance, the total heat dissipated can be calculated. EES software is used to solve the above equations of the heat sink and obtain the heat sink's best design based on material alloy and compare it with the pure aluminum material. Moreover, the ICEPAK CFD code was utilized to carry out the heat sink simulations.

3. Results and discussion

In the present study, the pin fin heat sink's thermal performance at a different type of alloy materials has been carried out as a function of the diameter. The model with Al- Cu, Al-Be pin fin heat sink compared with the pure aluminum material is analytically investigated. For all of the types of materials heat sinks, it is mounted that the hot spots at their centers. The results are evaluated by varying the pin fin heat sink model's diameter for all material types. The important parameter is the heat dissipated from the heat sink to surroundings plotted as a function of the fins' diameter for all the materials types, as shown in Figure 3. It can be observed that the rate of heat transfer rate increases as the diameter increases before it stabile and decreases with an increase in the fin diameter. This behavior can be attributed to the extra surface that increased with the increase in the fin diameter. While the decrease in the heat dissipated of heat sink started after 5 mm diameter, which can be ascribed to the increase in the pressure drop and decrease in the mass flow rate, consequently the heat dissipated decrease after 5 mm diameter. In terms of the material type, it can be observed that Al-Cu alloy has the highest heat transfer rate compared with the other types of heat sink materials. In contrast, the Al-Be alloy has the lowest value of the heat transfer rate. For instance, the heat dissipated increases by 1.4% using Al-Cu alloy instead of pure aluminium while the heat dissipated of the heat sink drops by 2% with using Al-Be instead of pure aluminium. This can be ascribed to the associate the change in thermal conductivity of the Al-Cu, which is greater than that of aluminium pure that leads to providing more heat storage capacity compared to pure aluminium. Moreover, the decrease in the thermal conductivity using Al-Be leads to the heat dissipation of the Al- Be was lower than that of the aluminium pure. Similar behavior was observed by many researchers such as [9][6][30][31]

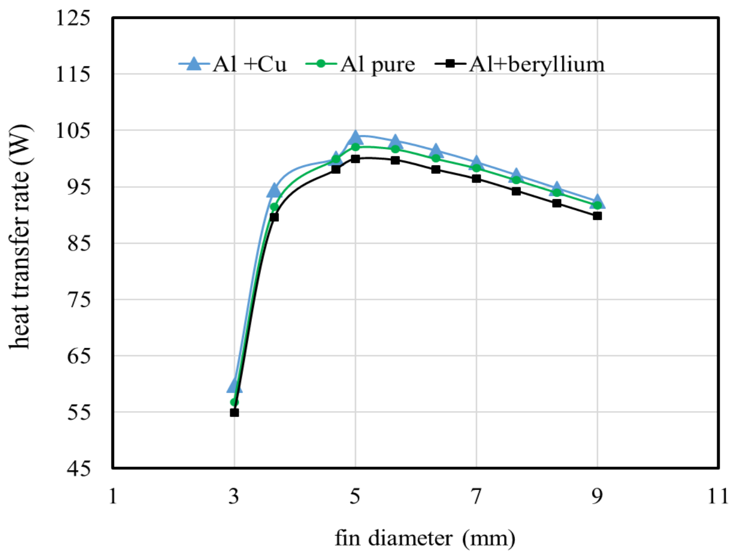

Figure 3. The heat transfer rate versus fin diameter for pin fin heat sink for all the material types.

The thermal resistance is essential that influences the performance of the heat sink. Figure 4 represents the system's thermal resistance behavior as a function of the diameter of the pin fin heat sink for different types of material. It can be seen from this Figure that, for all types of materials, the thermal resistance decreases as the diameter of the fins increase before it reaches the minimum value, then it increases with the increase in the fin diameter. This behavior can be attributed to the increase in the volume as the diameters of pin fins increases. Moreover, the thermal resistance decreases after 5 mm diameter, which can be attributed to the significant increase in the fin diameter. Consequently, the thermal resistance increases with an increase in the fin diameter. In terms of the heat sink material, it can be seen from the Figure the thermal resistance of the Al-Cu heat sink is higher than that of the Al-be and pure aluminium, respectively. For example, the thermal resistance of heat sink using Al-Cu is higher than that of pure aluminium at 1.5%. In comparison, the thermal resistance of heat sink using Al-be is lower than that of pure aluminium by 2%. The explanation of this behavior due to an increase in the thermal conductivity of Al-Cu and decreases for the Al-beryllium compared to the reference one.

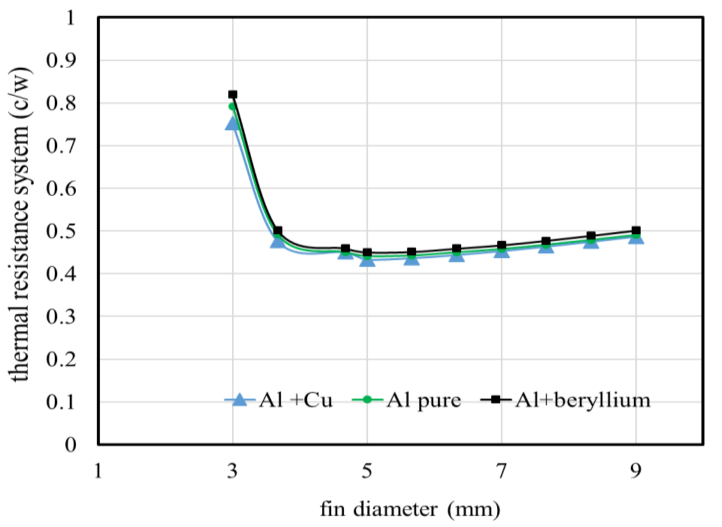

Figure 4. The resistance versus fin diameter for pin fin heat sink for all material types.

Figure 5 shows the efficiency of the fins sinks via fin diameter for pin-fin materials types. As shown in this figure, the fin heat sink's efficiency increases as the fin diameter increases. As mentioned, this is because the increase in the fin diameter provides more surface area. Moreover, the fins sink's efficiency of the Al-Cu heat sink has the highest value, while Al-beryllium and Al heat sink have the lowest value. It can also be noticed the fin efficiency of the heat sink for the Al-Cu is higher than that of the pure aluminium by 1.5%, while the thermal resistance of the Al-Be was lower than that of the pure aluminium by 2%. The explanation of this behavior can be ascribed to the increase in the thermal conductivity of Al-Cu and decreases for the Al-Be compared to the Al pure heat sink. This behavior was consistent with the result indicated by Khan et al. [6] and [9].

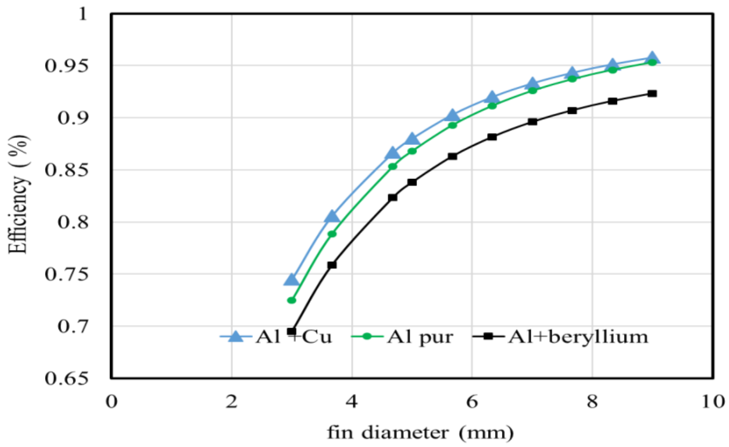

Figure 5. The efficiency versus fin diameter of the fin heat sink for all material types.

The mass of the heat sink is important; therefore, the pin fin heat sink's mass as a function of fin diameter is plotted, as shown in Figure 6. It can be noted that the mass of the heat sink increases gradually with the increase in the fin diameter. The explanation of this behavior can be ascribed to the increase in the volume of the fins. While for the material types, it can be seen the pure aluminium exhibits a lower mass than the Al – Cu and higher than that of the Al - Be alloy. This change in the heat sink mass was increased by 1.5% using Al-Cu alloy instead of pure aluminium, while the heat sink was decreased by 2.4% using Al- Be instead of pure aluminium. This is because the aluminium density is higher than that of the beryllium and lower than that of copper. This behavior was consistent with studies introduced by [6][9][24][8].

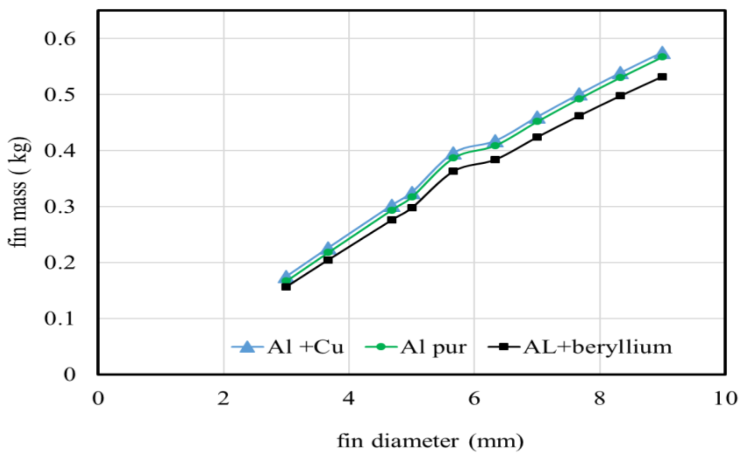

Figure 6. The relationship between the mass of heat sink and fin diameter for pin fin heat sink for all the material types.

The temperature distribution over a pure aluminium pin fin heat sink is also plotted as shown in Figures 7, 8, and 9, showing the temperature distribution for the heat sink using pure aluminium, Al-Cu, and Al – Be, respectively. It can be remarked that the best temperature and heat dissipated occurs using Al-Cu alloy compared with other types of material. This behavior was consistent with the results of the analytical study that is previously shown. It can be detected the maximum temperature near the heat source.

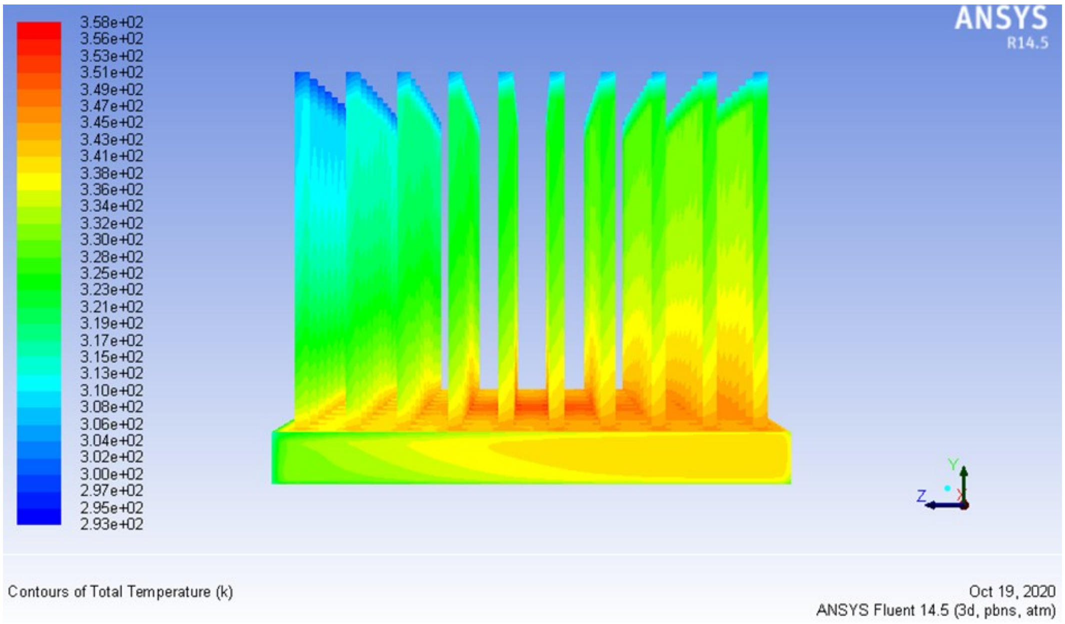

Figure7. The temperature distribution for the pin heat sink for pure Al.

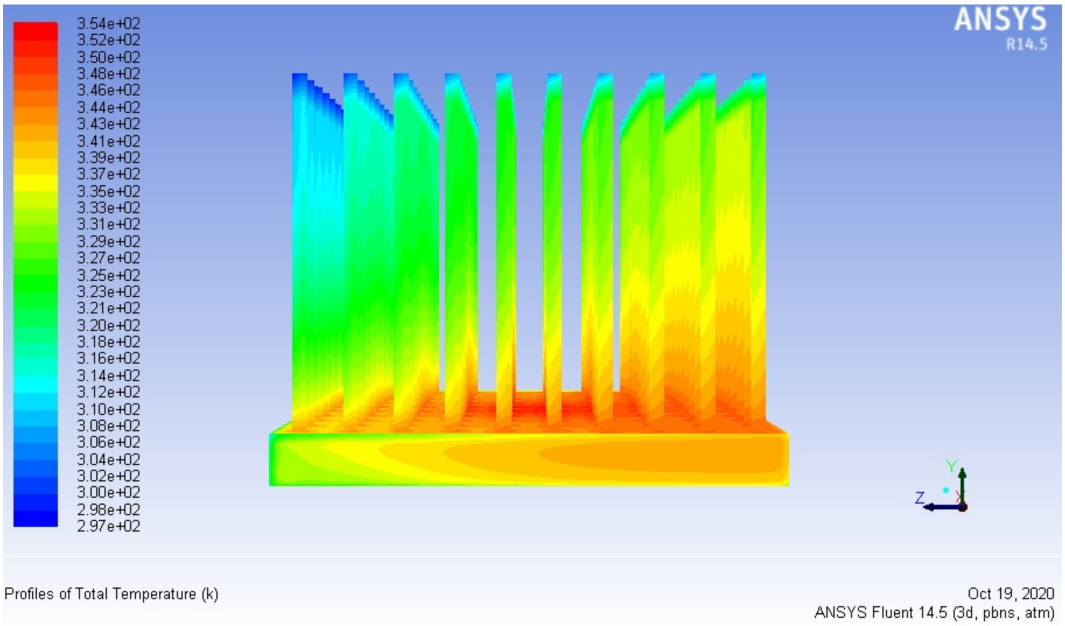

Figure 8. The temperature distribution for the pin heat sink for CU- Al.

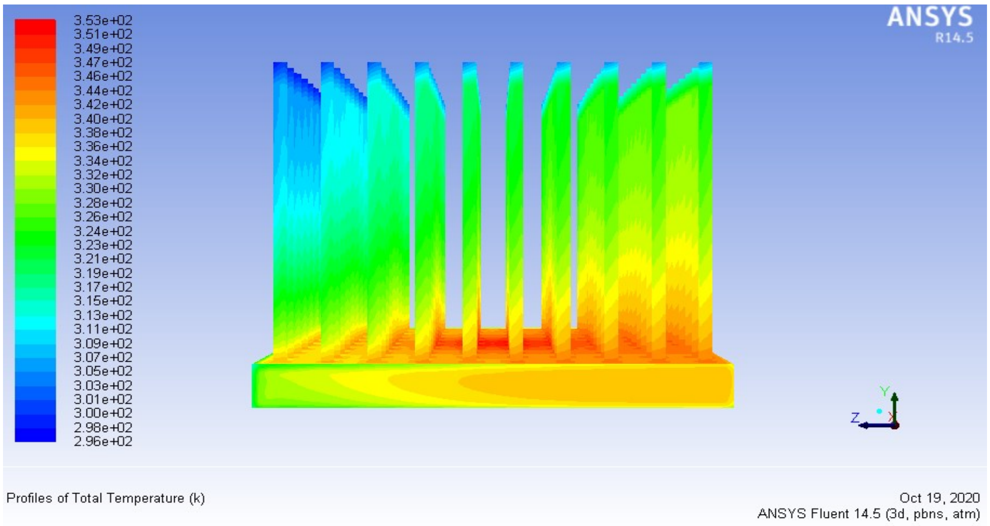

Figure 9. The temperature distribution for the pin heat sink for Be- Al.

4. Conclusions

The influence of the alloy materials on the pin fin heat sink's thermal performance has been studied in this work. Copper-aluminium, beryllium - aluminium was used and compared with pure aluminium. The analyses were performed by varying the diameter pin fin heat sink. It can be drawn from these obtained results.

- For the alloys materials and pure aluminium, the heat dissipated rate, mass of the heat sink, and fin efficiency increased with increasing the fin diameter.
- The heat dissipated rate of the heat sink using copper—aluminium was higher than that of using pure aluminium while heat dissipated rate of the heat sink using beryllium –aluminium was lower than that of the pure aluminium.
- Copper—aluminium alloy has the highest weight compare with pure aluminium. While beryllium – aluminium has the lowest weight compared with other material of the heat sink.
- It is also concluded that the copper—aluminium can be used as a substitute material for the heat sink material instead of the pure aluminium since it outperforms in terms of thermal performance on both that of the pure aluminium and beryllium - aluminium.

Nomenclature

A	Surface area, (m^2)	μ	Dynamic viscosity, (kg/m.s)
cp	specific heat, (kJ/kg.K)	η	Efficiency, (%)
D	Diameter, (m)	∞	Infinity
H	Height, (m)	Subscripts	
h	Heat transfer coefficient ($W/m^2.K$)	a	approach
K	Thermal conductivity, (W/m.K)	HS	Heat sink
L	Length, (m)	J	Junction
n	Number of fins, (-)	L	Longitudinal
Pr	Prandtl number, (-)	max	maximum
q	Heat transfer rate, (Watt)	T	Transverse
R	Thermal resistance (K/W)	Abbreviations	
Re	Reynolds number, (-)	Al	aluminum
S	Space between fins, (m)	Be	Beryllium
T	Temperature, ($^{\circ}C$)	CFD	Computational fluid dynamic
U	Mean velocity, (m/s)	Cu	Copper
W	width, (m)	EES	Engineering equation solver
Greek symbols		LED	Lighting emitted diode
γ	Aspect ratio, (-)		

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