Effect of heat sink design on the thermal characteristic in computational fluid dynamics analysis

C Y Khor¹, M A M Nawi¹, Muhammad Ikman Ishak¹, W C Kee¹, M U Rosli¹, Mohd Riduan Jamalludin³ and S N A Ahmad Termizi³

¹Simulation and Modelling Research Group (SimMReG), Faculty of Engineering Technology, Universiti Malaysia Perlis (UniMAP), Kampus UniCITI Alam, Sungai Chuchuh, Padang Besar, 02100 Perlis Indera Kayangan, Malaysia
²Faculty of Engineering Technology, Universiti Malaysia Perlis (UniMAP), Kampus UniCITI Alam, Sungai Chuchuh, Padang Besar, 02100 Perlis Indera Kayangan, Malaysia
³E-mail: cykhor@unimap.edu.my

Abstract. The thermal management in the electronic device or system using the heat sink is important to ensure the device or system operating under the allowable temperature. The present study aims to investigate the thermal characteristic (i.e., temperature distribution) of the various heat sink designs via computational fluid dynamics (CFD) analysis. The electronic cooling process of the heat sink is carried out via CFD software. The temperature distribution of the various heat sink designs (i.e., plate fin, circular pin fin and rectangular fin) was analyzed and compared. The CFD analysis revealed the plate fin heat sink has lowest temperature distribution on the fin region. High temperature distribution was observed on the pin fin heat sink. The non-uniform temperature distribution was attributed by the direction of inlet airflow, whereas the low temperature was found in the region that close to the inlet airflow. Thus, the research findings indicated the design of heat sink significantly affects the temperature distribution during the electronic cooling process.

1. Introduction

Heat sink is a main component in the electronic device or system using the heat sink is important to ensure the device or system operating under the allowable temperature. The present study aims to investigate the thermal characteristic (i.e., temperature distribution) of the various heat sink designs via computational fluid dynamics (CFD) analysis. The electronic cooling process of the heat sink is carried out via CFD software. The temperature distribution of the various heat sink designs (i.e., plate fin, circular pin fin and rectangular fin) was analyzed and compared. The CFD analysis revealed the plate fin heat sink has lowest temperature distribution on the fin region. High temperature distribution was observed on the pin fin heat sink. The non-uniform temperature distribution was attributed by the direction of inlet airflow, whereas the low temperature was found in the region that close to the inlet airflow. Thus, the research findings indicated the design of heat sink significantly affects the temperature distribution during the electronic cooling process.

With the aid of the computational analysis, the simulation model could mimic the actual condition for different case studies such as in heat transfer of infrared reflow oven [9], heat sink [10], integrated circuit encapsulation process [11-13], reflow soldering process [14, 15] and wave soldering [16]. In the simulation analysis, the various discretization methods include finite element (FE) and finite volume (FV) [17, 18]. Similarly, the cooling of a heat sink can be performed via simulation analysis. The thermal performance of the heat sink was affected by the fin width, fin height and Reynold number [19]. As Reynolds numbers rise, the thermal resistance of heat sink tends to be reduced. The
fin width that provided the optimum thermal resistance as the Reynolds number increased with constant fin height unless further increases the fin width which will reduce their performance. The cross cut length of the heat sink crucially influence the thermal performance [20]. Besides, the evaluation of thermal performance of the heat sink with extrusion fin, plain fin, and cell fin was reported by Yeh [21]. They found various fin designs play an important role in the characteristics of the heat sink.

In this research work, the plate fin, circular pin fin and rectangular fin heat sink were considered to study the thermal characteristics (i.e., temperature distribution) by using computational fluid dynamics (CFD) method [9]. The CFD software was employed to construct the heat sink and simulate the heat sink cooling process in a CFD domain. The evaluation of the simulation results is focused on the temperature distribution in different position of the heat sink.

2. Methodology

Three different heat sink designs, namely, plate fin, circular pin fin and rectangular fin were constructed in the CFD software according to the dimension of the heat sink as summarized in Table 1. Figure 1 depicts the three-dimensional (3D) model of the heat sinks. The rectangular fluid domain was constructed to define the inlet and the outlet boundary for the cooling process, while the heat sink is located at the center of the domain. In the cooling process, the 1 m/s of air flows in longitudinal direction which enter from the inlet and exit at the outlet. The constant heat flux (500W/m²) was applied at the bottom of the heat sink.

| Dimension/Unit (mm) | Plate fin | Circular pin fin | Rectangular fin |
|--------------------|-----------|-----------------|-----------------|
| Heat sink length (L) | 100       | 100             | 80              |
| Heat sink width (W)  | 60        | 60              | 50              |
| Heat sink height (H) | 41        | 41              | 41              |
| Base height (Hb)     | 1         | 1               | 1               |
| Fin height (Hf)      | 40        | 40              | 40              |
| Fin thickness (t)    | 2         | 6               | 2               |
| Number of fin        | 4         | 12              | 35              |

In the CFD simulation, the continuity equation, momentum equations and energy equation [7-9] were considered to model the motion of airflow passing through the heat sink. The airflow was assumed as a laminar, incompressible and steady state flow. SIMPLE scheme and 2nd order upwind discretization [9] were considered in the setting CFD software. The simulation converged when the residuals reach 1E-6. The temperature distribution during the cooling process is analyzed for each heat sink from the simulation results.
3. Results and discussion
The CFD simulation results were analyzed based on the contour of temperature and the temperature at various positions of the fin. Figure 2 shows the contour of temperature and the temperature measured at different positions of the fin. The simulation results revealed the non-uniform temperature distribution on the plate fin heat sink (Figure 2a). It was observed that the temperature around the inlet region is much lower than the outlet region. The heat remains higher at outlet region shows that lesser heat was carried away from the model. Besides, the outside regions between the left and right of heat sink base plate were investigated. The temperature at different positions are plotted in Figure 2(b). The comparison of temperature noticed that the top region of the heat sink has the lowest temperature among these three positions. This is attributed by the airflow, which carry more heat out from the heat sink.

The simulation results of the circular pin fin and rectangular fin heat sink were analyzed. The contour of temperature and temperature plot at various positions for circular pin and rectangular fin were studied as shown in Figures 3 and 4. A similar phenomenon was observed that the inlet region has a lower temperature compared with the outlet region. High temperature is distributed in the region that closer to the outlet. The shape of the fin may also affect the effectiveness of the heat transfer of the heat sink. This is because of the circular pin fin acting as the obstruction, hence induced the curvy flow that affect the cooling of heat sink that close to outlet region. Besides, the other phenomenon was observed in the simulation results, the increasing of the total convective surface area of the rectangular fin heat sink resulted in the greater pressure drop along the heat sink. At the same time, the velocity of air passing through the heat sink declined. This situation directly affects the cooling of the heat sink.

Five locations on the heat sink were considered to measure temperature during the cooling process (Figure 5). The comparison of the temperature of different heat sink designs indicated that circular pin fin has the greatest temperature compared to other heat sinks. The curvy airflow due to the circular pin fin causing less heat is carried away from the heat sink, especially around the outlet region. The simulation results indicated that plate fin heat sink has lowest temperature distribution. This may due to the smooth airflow passing through the heat sink. Thus, more heat was carried away from the plate fin heat sink. On the other hand, the Analytical Hierarchy Process (AHP) [22-24] is also one of the alternative approaches that can be applied in the design process of the heat sink to determine the suitable fabrication process of the heat sink. Besides, the mechanical aspects [25] such as stress, strain and displacement endured to heat sink can be analyzed via the finite element method [26, 27] and the method of parametric study to investigate the effect of factor [28-30].

Figure 2. (a) Temperature distribution contour and (b) temperature at various positions of plate fin heat sink.
Figure 3. (a) Temperature distribution contour and (b) temperature at various positions of circular pin fin heat sink.

Figure 4. (a) Temperature distribution contour and (b) temperature at various positions of rectangular fin heat sink.

Figure 5. (a) Location of measurement and direction of airflow, and (b) comparison of temperature for three different heat sink designs.
4. Conclusion
The effect of heat sink design on the thermal characteristic has been studied via computational fluid dynamic simulation. The current results noticed that the design of heat sink significantly influences the temperature distribution during the electronic cooling process. The shape of fin also leads to the vortex generation and curvy airflow that reduce the effectiveness of cooling compared to plate fin heat sink. The comparison study revealed the plate fin heat sink yield lowest temperature distribution during the cooling process. Thus, the current result is expected to provide basic understanding to the engineer in the design process of heat sink for the purpose of thermal management in an electronic device or system. The current research work is expected to extend by considering various factors such as heat flux, inlet velocity and Sandra heat sink.

5. References
[1] Bassiony R, Maher H and Hegazy A 2016 Applied Thermal Engineering 99 273-279
[2] Li H and Chao S 2009 International Journal of Heat and Mass Transfer 52(13-14) 2949-2955
[3] Dogruoz M, Urdaneta M and Ortega A 2005 International Journal of Heat and Mass Transfer 48(23-24) 5058-5071
[4] Jeng T and Tzeng S 2007 International Journal of Heat and Mass Transfer 50(11-12) 2364-2375
[5] Park S, Jang D, Yook S and Lee K 2015 International Journal of Heat and Mass Transfer 87 184-188
[6] Li B, Baik Y and Byon C 2016 Energy Conversion and Management 108 422-428
[7] Abdul Aziz M S, Abdullah M Z, Khor C Y, Jalar A and Che Ani F 2014 International Journal of Heat and Mass Transfer 72 400-410
[8] Khor C Y, Abdullah M K, Abdullah M Z, Abdul Mujeebu M, Ramdan D, Majid M F M A and Arif Z M 2010 Heat and Mass Transfer/Waerme- und Stoffuebertragung 46 1315-1325
[9] Najib A M, Abdullah M Z, Khor C Y and Saad A A 2015 International Journal of Heat and Mass Transfer 87 49-58
[10] Zhao J, Huang S, Gong L and Huang Z 2016 Applied Thermal Engineering 93 1347-1359
[11] Khor C Y and Abdullah M Z 2012 Simulation Modelling Practice and Theory 29 109-122
[12] Khor C Y, Abdullah M Z, Lau C-S, Leong W C and Abdul Aziz M S 2014 Microelectronics Reliability 54(4) 796-807
[13] Khor C Y and Abdullah M Z 2013 Microelectronics Reliability 53(2) 334-347
[14] Lau C-S, Abdullah M Z and Khor C Y 2013 Microelectronics International 30(3) 151-168
[15] Lau C S, Khor CY, Soares D, Teixeira J C and Abdullah M Z 2016 Soldering and Surface Mount Technology 28(2) 41-62
[16] Abdul Aziz M S, Abdullah M Z, Khor C Y, Fairuz Z M, Iqbal A M, Mazlan M and Rasat M S M 2014 Advances in Mechanical Engineering 2014 275735
[17] Ramdan D, Abdullah M Z, Khor C Y, Leong W C, Loh W K, Ooi C K and Ooi R C 2012 IEEE Transactions on Components, Packaging and Manufacturing Technology 2(11) 1786-1795
[18] Ong E E S, Abdullah M Z, Khor C Y, Loh W K, Ooi C K and Chan R 2014 Microelectronic Engineering 113 40-49
[19] Li H and Chao S 2009 International Journal of Heat and Mass Transfer 52(13-14) 2949-2955
[20] Kim T and Kim S 2009 International Journal of Heat and Mass Transfer 52(23-24) 5358-5370
[21] Yeh L-T 2012 13th InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, San Diego, CA, 2012 446-449
[22] Rosli M U, Jamalludin M R, Khor C Y, Ishak M I, Jahidi H, Wasir N Y, Faizal W M, Draman W N A W, Lailina N M and Ismail R I 2017 MATEC Web Conf. 97 01039
[23] Luqman M, Rosli MU, Khor CY, Zambree S, Jahidi H 2018 IOP Conf. Series: Materials Science and Engineering 318 012058
[24] Rosli M U, Ariffin M K A, Sapuan S M and Sulaiman S 2013 International Journal of Engineering and Technology 5(3) 3158-3167
[25] Ishak M I, Abdul Kadir M R, Sulaiman E and Kasim N A 2010 *Proceedings of 2010 IEEE EMBS Conference on Biomedical Engineering and Sciences*, IECBES 2010 5742230 210-215
[26] Ishak M I, Ahmad Shafi A, Abdul Kadir M R and Sulaiman E 2017 *Journal of Medical and Biological Engineering* 37(3) 336-344
[27] Ishak M I and Abdul Kadir M R 2013 *SpringerBriefs in Applied Sciences and Technology* 9783642326028 9-26
[28] Harun Z, Jamalludin M R, Basri H, Shohur M F, Rosman N, Yunos M Z 2013 *Jurnal Teknologi*, 65(4) 121-125
[29] Yunos M Z, Harun Z, Basri H, Shohur M F, Jamalludin M R, Hassan S 2013 *Jurnal Teknologi* 65(4) 117-120
[30] Yunos M Z, Harun Z, Basri H, Shohur M F, Jamalludin M R, Hassan S, Ismail A F 2013 *Jurnal Teknologi* 65(4) 111-115