Investigation of water cooled aluminium foam heat sink for concentrated photovoltaic solar cell

Weng Cheong Tan¹, Lip Huat Saw¹*, Hui San Thiam¹, Farazila Yusof², Chin-Tsan Wang³, Ming Chian Yew¹ and Ming Kun Yew¹

¹ Lee Kong Chian Faculty of Engineering and Science, UTAR, 43000, Kajang, Malaysia.
² Department of Mechanical Engineering, University of Malaya, 50603, Malaysia.
³ Department of Mechanical and electro-mechanical Engineering, National I-Lan University, I-Lan, Taiwan.
E-mail: sawlh@utar.edu.my, bernardsaw81@yahoo.com

Abstract. Concentrated photovoltaic cell (CPV) is a popular renewable source nowadays. It has high efficient yet cost effective energy harvesting system available in the market. The performance of the CPV depends strongly on the temperature of the solar cell. The efficiency reduces as the surface temperature of the CPV increases. It is crucial to reduce the temperature of the CPV and maintains a small temperature variation along the surface of the CPV. Metal foam is an ideal solution for a CPV thermal management system. It helps to enhance the mixing of coolant due to its porous characteristics and lead to higher heat transfer rate and reduce the overall average temperature of a CPV. The main objective of this study is to enhance the heat removal rate along of the CPV. Aluminium foam is used as a heat sink to removal the heat generated. The effects of porosities and pores density (PPI) of the aluminium foam are measured against the thermal performance. Computational thermal fluid dynamics is conducted to study the thermal performance of aluminium foam heat sink. The parameters required for the simulations are extracted from literature. The results suggested that aluminum foam is able to enhance the heat removal and maintains better temperature uniformity of the CPV. 10PPI aluminum foam with porosity 0.682 provides the most optimum results with average temperature of 55.1 ºC and temperature different of 7.4 ºC at flow rate of 40 g/s. This approach is suitable to promote the efficiency of the CPV and prolong the cycle life.

1. Introduction
Recently, solar energy has been received attention globally. It is a type of renewable sources that is free, non-polluting and exist abundantly. Development of solar energy harvesting system is important as it can help to convert light energy from solar radiation into electrical energy for commercial application. Besides that, government from various countries start to rely on solar energy for electricity generation. There are numerous method to harvest solar energy such as photovoltaic cell, solar pond, solar concentration systems and solar thermal collectors. Using concentrated photovoltaic (CPV) is an efficient ways to extract electrical energy from solar energy.

Compare to other type of solar cell, high efficiency CPV has gain attention from researchers. However, overheating issue is a main drawback to promote the use of the CPV. When the temperature is too high, the efficiency of the solar system is dropped. Previous study suggested that for one degree increased in temperature, the efficiency drops by 0.45% [1]. A maximum temperature of 1400 ºC can be reached when a solar cell was subjected to 500 suns concentration and fully insulated [2]. This
temperature is a lot higher than the suggested operating temperature of a CPV which is 100 °C [3]. The high temperature can damage the system and cause breakdown. Hence, an effective thermal management system is needed to maintain the temperature uniformity of CPV. Some of the important design criteria for the CPV cooling system are cell temperature, reliability, temperature uniformity, pumping power, material efficiency and usability of thermal energy.

Passive cooling is an affordable and simple method. However, the performance is weak and depend on wind blow and required heat sink with large area [4]. On the other hand, a more effective cooling method for CPV is using forced convection with air and water will be used as a coolant. Due to high specific heat capacity of water, water can dissipate more heat than air and it is more suitable for CPV with high sun concentration. Microchannel heat sink was used to cool the CPV system by Radwan et al. [5]. Compared to other cooling method, water cooled CPV with microchannel was able to achieve the highest performance. Siyabi performed an analysis to study the effect of multi-layer microchannel on thermal performance of a CPV [6]. Water was used as a coolant. The result revealed that the thermal resistance, pressure drop and temperature variation was dropped as a result of increasing the multi-layer microchannel. Moreover, a multilayer manifold microchannel heat sink to cool a CPV system was conducted by Yang et al. [7]. Study revealed that the surface temperature variation was reduced. All the study suggested that microchannel is able to reduce average temperature and maintain temperature uniformity of a CPV.

Metal foam is a material which has good mechanical properties and heat transfer characteristics [8]. The internal structure of the metal foam is complex. It has high surface area per unit volume. This is an ideal candidate for heat transfer application which metal foam provided tortuous flow path and promote mixing. The coolant tends to mix which result in promoting the heat transfer rate. Metal foam was widely used for thermal management application due to its excellent performance in heat transfer [9]. The application of metal foam as a heat sink in CPV is rarely investigated. Flirsanov used open cell aluminum foam to cool the CPV receiver and the cell performance was studied [10]. The cell efficiency was improved for about 0.5% while the electrical generation increased by 1.5%. This showed that metal foam is suitable to be applied as a heat sink for a solar harvesting system.

In this study, aluminum metal foam with different mechanical properties will be used to cool the CPV with water as cooling fluid. The thermal performance will be measured in terms of average temperature and temperature uniformity. The objective is to achieve a low average temperature. Numerical study will be conducted to compare the performance among all of the metal foam sample. Total seven metal foam samples with 10 PPI, 20 PPI and 40 PPI and different porosity will be tested and measured its thermal performance. The parameter needed for simulation such as heat transfer correlation, permeability and inertia coefficient are extracted from the literature. Finally, a metal foam which give the best performance will be proposed for the heat sink design.

2. Numerical modelling

Fig. 1 shows The CAD model used in the simulation. The metal foam heat sink has a size of 30 mm (L) x 30 mm (W) x 6.25 mm (T). The heat sources of the system was simulated using a 2 mm copper square block with dimension of 30mm (L) x 30mm (W). The aluminium metal foam used in this study is manufactured by ERG aerospace Corp. Water is used as a coolant in the study.

2.1 Parameter extraction

Seven pieces of aluminium metal foam with different porosity and pores density will be studied and its physical characteristics were summarized in Table 1. The physical and thermal properties were extracted from literature [11]-[12]. Metal foam with low porosity (<90%) was compressed metal foam.
Figure 1. CAD model of metal foam heat sink.

Table 1. Characteristics of Duocell Aluminum Foam.

| Sample | PPI | Porosity | Surface area per unit volume of foam (m²/m³) | Permeability (x 10⁻⁸ K, m²) | Inertia coefficient, °F (10⁻¹) |
|--------|-----|----------|---------------------------------------------|--------------------------------|-------------------------------|
| A      | 10  | 0.918    | 809.1                                       | 10.10                          | 0.7                           |
| B      | 10  | 0.794    | 2053.1                                      | 2.20                           | 1.28                          |
| C      | 10  | 0.682    | 3169.3                                      | 1.04                           | 1.78                          |
| D      | 20  | 0.924    | 1240.2                                      | 6.07                           | 0.72                          |
| E      | 20  | 0.774    | 3593.7                                      | 1.05                           | 2.1                           |
| F      | 20  | 0.679    | 5104.3                                      | 0.67                           | 2.5                           |
| G      | 40  | 0.918    | 1800.8                                      | 4.54                           | 0.82                          |

*a Compressed Aluminum foam

Interfacial heat transfer coefficient determines the heat transfer performance of the aluminum foam. The interstitial heat transfer coefficient of the aluminum foam with water was extracted from the work by Noh et al. [13]. This coefficient was further proof by A.M. Bayomy to be valid [14] and it was tabulated in Table 2. The equation for the heat transfer coefficient is shown in equation 1.

\[ h = C\dot{m}^b \] (1)

Table 2. Coefficient of heat transfer versus water mass flow rate.

| Sample | C    | b     |
|--------|------|-------|
| A      | 42285| 0.4   |
| B      | 36676| 0.4   |
| C      | 34194| 0.4   |
| D      | 34690| 0.4   |
| E      | 30144| 0.4   |
| F      | 32863| 0.4   |
| G      | 39246| 0.4   |
2.2 Numerical Procedure
The numerical study was conducted using commercial CFD software ANSYS-CFX. Total heat flux of 100 W/cm² was assigned on the heat sources. Water was used as a coolant with medium turbulence of 5%. The inlet mass flow rate was vary from 20g/s to 60g/s. The inlet temperature of the water was set as 30 °C. Shear Stress Transport (SST) turbulence model was used to characterize the flow in the metal foam [15]. The convergence criteria was set below 10⁻⁶ for the flow and energy equations while high resolution discretization scheme was used for better accuracy of the result.

2.3 Mesh independent test
Mesh independent test is needed to ensure reliability of the simulation results. The relative error should be as small as possible. The numerical study started by performing mesh independent test and the result is summarized as below. When comparing mesh 1 and mesh 2, it was found that the maximum relative error for the average temperature is about 2.63%. This value is reduced to 0.59% when the mesh is double as indicated by mesh 3. All the relative errors obtained are small than 2%. Therefore, mesh 2 is sufficient to provide a trustable results.

Table 3. Mesh Independent Test.

| Parameter                              | Mesh 1   | Mesh 2   | Relative error, % | Mesh 3   | Relative error, % |
|----------------------------------------|----------|----------|-------------------|----------|-------------------|
| No. of elements                        | 2645508  | 5307199  |                   | 1069977  |                   |
| Average temperature on the heat source surface, °C | 115.861  | 112.813  | 2.63              | 112.147  | 0.59              |
| Variation of temperature on the heat source surface, °C | 14.832   | 14.637   | 1.31              | 14.383   | 1.74              |
| Pressure drop, Pa                      | 1043.5   | 1052.4   | 0.85              | 1048.8   | 0.35              |

3. Results
From the simulation result, both porosity and pores density of the metal foam affects the heat transfer characteristics. From Fig. 2(a), the average temperature reduces with reducing porosity at fixed pores density. Reduction in average temperature indicates higher heat removal rate. When porosity reduces, aluminium foam has higher surface area, which increase the heat transfer area and lead to higher heat transfer rate. Besides that, the permeability tends to reduce with low porosity. Low permeability traps more coolant within the internal structure of the metal foam. This leads to more vigorous mixing of coolant and hence, promoting the redevelopment of the thermal boundary layer and improve heat transfer coefficient. When comparing the metal foam with high porosity (>90%), increasing the pores density will reduce the average temperature as shown in Fig 2(a). 20PPI aluminum foam with porosity 0.682 performs the best in heat transfer. On the other hand, 10PPI aluminum foam and porosity 0.918 performs the worst in heat transfer.

Fig 2(b) shows the results for temperature uniformity versus the mass flow rate. Increasing the mass flow rate is able to reduce the temperature variation. When compared only 10 PPI aluminum foam, reducing the porosity will cause lower temperature difference, which is favor for the CPV system. For flow rate from 30g/s to 60g/s, aluminum foam with pores density of 10PPI and porosity of 0.918 shows no improvement in reducing temperature variation. It reaches its maximum cooling capacity. Moreover, the temperature uniformity for 20PPI aluminum foam with porosity 0.924 maintains at 13.5 °C when water mass flow rate is increases from 40 g/s to 60 g/s. For high porosity metal foam, it can be observed that increasing the pores density will lead to poor temperature variation as observed at flow rate of 20 g/s. At porosity of 0.918, 10 PPI metal foam possess temperature difference of 14.4 °C while 40 PPI metal foam with porosity of 0.918 has temperature difference of 17.2 °C. Hence, high pores density causes higher temperature uniformity at similar porosity. In general, 20 PPI aluminum foam has higher temperature variation as compared to 10PPI for all...
porosities. In short, 10 PPI metal foam with porosity of 0.682 is able to provide better temperature variation among all the sample at same flow rate.

![Figure 2.](image.png)

**Figure 2.** (a) Average temperature (b) Variation of temperature of 20PPI metal foam with porosity of 0.679.

Increasing the mass flow rate to produce higher performance in heat transfer is not favorable due to higher pressure drop. A careful selection of properties of metal foam is required when designing a heat sink for a CPV system to achieve the best performance. In summary, aluminum foam with 20PPI and 0.679 porosity provides a good heat transfer rate which in turns reducing the average surface temperature. In 10 PPI aluminum foam, 0.682 porosity is able to provide better temperature uniformity. 10PPI aluminum foam with porosity 0.682 is the optimized design which find a balance among average temperature and temperature uniformity. At flow rate of 40g/s, it has average temperature of 55.1 °C and temperature variation of 7.4 °C.

4. Conclusion

This study concluded that aluminum metal foam is suitable to be used as heat sink of CPV. It can help to improve the thermal management of a system. Low porosity aluminum foam helps to improve heat transfer rate and lead to higher thermal performance. Aluminum foam with high pores density promotes redevelopment of the thermal boundary layer which result in better heat transfer performance. However, it can leads to extra pressure loss when low porosity and high pores density metal foams is used as a heat sink. Therefore, an optimization process is needed to compromise the effect of pores density and porosity with the average temperature and temperature variation as well as pressure drop. 10PPI aluminum foam with porosity 0.682 is the optimized design for the study. In the future work, an optimized functionally graded metal foam heat sink will be produced. The new type of heat sink will possess different characteristics along the flow channel from the upstream to the downstream. It is forecast that it can help to achieve a higher heat transfer performance compare to conventional metal foam heat sink.

Acknowledgements

This work is supported by Fundamental Research Grant Scheme (Grant No. FRGS/1/2018/TK07/UTAR/02/4) from Ministry of Higher Education Malaysia and University of Malaya RU Grant with Project No: ST006-2018.
References

[1] Ye Z, Li Q, Zhu Q and Pan W 2009 The cooling technology of solar cells under concentrated system 2009 IEEE 6th International Power Electronics and Motion Control Conference, IPEMC ’09.

[2] Araki K, Uozumi H and Yamaguchi M 2002 A simple passive cooling structure and its heat analysis for 500X times; concentrator PV module Conf. Rec. Twenty-Ninth IEEE Photovolt. Spec. Conf.

[3] Segev G, Mittelman G and Kribus A 2012 Equivalent circuit models for triple-junction concentrator solar cells Sol. Energy Mater. Sol. Cells.

[4] Zou Z, Gong H, Wang J, and Xie S 2017 Numerical Investigation of Solar Enhanced Passive Air Cooling System for Concentration Photovoltaic Module Heat Dissipation Journal of Clean Energy Technologies.

[5] Radwan A, Ookawara S and Ahmed M 2016 Analysis and simulation of concentrating photovoltaic systems with a microchannel heat sink Sol. Energy.

[6] Siyabi I Al, Shanks K, Mallick T and Sundaram S 2017 Thermal analysis of a multi-layer microchannel heat sink for cooling concentrator photovoltaic (CPV) cells AIP Conference Proceedings.

[7] Yang K and Zuo C 2015 A novel multi-layer manifold microchannel cooling system for concentrating photovoltaic cells Energy Convers. Manag.

[8] Lefebvre L P, Banhart J and Dunand D C 2008 Porous metals and metallic foams: Current status and recent developments Adv. Eng. Mater.

[9] Tan W C, Saw L H, Thiam H S, Xuan J, Cai Z and Yew M C 2018 Overview of porous media/metal foam application in fuel cells and solar power systems Renew. Sustain. Energy Rev.

[10] Flitsanov Y and Kribus A 2018 A cooler for dense-array CPV receivers based on metal foam Sol. Energy.

[11] Hernandez ARA 2005 Combined flow and heat transfer characterization of open cell aluminium foams [Master thesis] University of Puerto Rico.

[12] Saw L H, Ye Y, Yew M C, Chong W T, Yew M K and Ng T C 2017 Computational fluid dynamics simulation on open cell aluminium foams for Li-ion battery cooling system Appl. Energy.

[13] Noh J S, Lee K B and Lee C G 2006 Pressure loss and forced convective heat transfer in an annulus filled with aluminum foam Int. Commun. Heat Mass Transf.

[14] Bayomy A M, Saghir M Z and Yousefi T 2016 Electronic cooling using water flow in aluminum metal foam heat sink: Experimental and numerical approach Int. J. Therm. Sci.

[15] Canonsburg T D 2012 ANSYS CFX-Solver Manager User ’ s Guide Knowl. Creat. Diffus. Util.