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Microscale Electromagnetic Actuation of Ferrofluid for Enhanced Cooling Efficiency

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***Abstract*—Efficient cooling solutions can greatly enhance the performance and reliability of electronic systems. Traditional cooling methods have been well-developed, but most are based on not highly efficient cost-effective conduction heat exchange. Improving heat exchange efficiency at low cost is a crucial task for all cooling applications. In this paper, we propose a novel method to improve heat exchange efficiency based on ferrofluid, a fluid with ferromagnetic properties, as a coolant. As a result, conduction heat exchange can be easily transformed into convection heat exchange in a passive manner with no additional energy required, significantly increasing cooling efficiency at a relatively low cost. A cooling system using ferrofluid as a coolant is designed and applied to a multi-junction ,or concentrated, photovoltaic and thermal (CPV/T) system through CFD modelling. Novel unsteady flow is generated resulting in higher thermal efficiency. Since ferrofluid is a nanoparticle, the proposed cooling method can be downsized to micro- or nano-scales for potential applications in many new areas.**

***Index Terms*—Special Machines, Electromagnetic Actuators and Sensors (ferrofluid, thermal management, cooling system, CPV)**

I. Introduction

In power electronic systems, uncontrolled elevated temperature is one of the main factors that can lead to system faults and eventual failure. Therefore, the reliability of these systems heavily relies on the thermal management of the system. Cooling technologies have been a subject of research in power electronics, with different cooling technologies using solid, gas, liquid and two-phase materials being developed and applied to various types of power electronic systems. Photovoltaic (PV) panels are a typical power electronic system, and the cooling of PV panels is a crucial aspect of the design. Concentrated Photovoltaic (CPV) is a more advanced type of PV made with a multi-junction structure, resulting in higher solar efficiency and also higher operation temperature. Several cooling methods have been developed to achieve lower system temperatures and better temperature uniformity. Currently, cooling methods for Concentrated Photovoltaic and Thermal (CPV/T) systems, such as heat pipe cooling, micro-channel cooling, and liquid immersion cooling, mainly use water as a coolant and focus on improving the structure of the cooling system. Heat pipes are passive two-phase heat transfer devices that have been known for more than 50 years and have been continuously developed since then, leading to modern high performance implementations. The performance limits of heat pipes and vapor chambers are currently an area of research. For CPV systems, the transient and steady-state behavior of flat-type heat pipes has been investigated experimentally, and some theoretical and numerical models related to flat heat types and loop heat pipes have been presented in literature [1]. Tarabsheh et al. [2] studied the effect of temperature variation on the performance of PV modules with heat pipe cooling and modeled the effect of non-uniform cooling. Huang et al. [3] proposed and examined the performance of a novel hybrid-structure heat pipe composed of sintered capillary and coronary-stent-like supporting structure for concentrated photovoltaic systems. The thermal resistance was reduced by 65% compared to the design without a supporting structure. Additionally, the electrical efficiency of CPV was enhanced by 3.1% compared to an aluminum substrate. Li et al. [4] investigated a heat pipe radiator to eliminate non-uniform heat transfer across the surface of a CPV panel. However, challenges remain for water-based coolant cooling systems, as the conduction heat exchange method of water coolant is inefficient, and systems to generate turbulence are either too cumbersome or cost-ineffective. In this paper, we propose a ferrofluid-based cooling method. This method passively changes the conduction heat exchange to convective heat exchange by using ferrofluid as a coolant.

Ferrofluid, known as a ferromagnetic nanofluid, can respond immediately to an external magnetic field due to its superparamagnetic properties. However, it maintains its fluid state even under the application of a strong magnetic field instead of becoming a quasi-solid [5]–[7]. Due to its special properties, ferrofluid offers a novel way to improve cooling efficiency by changing the heat exchange method from conduction to convection [8], [9]. A permanent magnetic field is applied vertically to the pipe of the cooling system, which actuates the ferrofluid in the vertical direction, creating turbulence and improving the heat exchange efficiency. Therefore, this study focuses on investigating the application of a dynamic cooling system using ferrofluid as a coolant to achieve better cooling effects on power electronic systems [10]. The influence of an external magnetic field on the cooling system of a CPV system is evaluated. A three-dimensional finite element-based model is built to analyze the fluid behavior and the cooling efficiency of the proposed method.

II. MODELS

In the current study, a three-dimensional finite element-based simulation model was carried out. The mechanism of how the system works is shown in Fig.1. In this system, a heat sink was used. The heat sink is an aluminum block measuring 40mm in length, 40mm in width, and 10mm in height. The block consists of five circular microtubes with a diameter of D=4mm. There is a uniform and constant heat flux through the bottom face of the block, which serves as the only heat source. The side walls of the block were considered as adiabatic. An external magnetic field was generated by a U-shaped magnet. The field is uniform, and the dimension of the magnet is large enough to cover the entire heat sink.

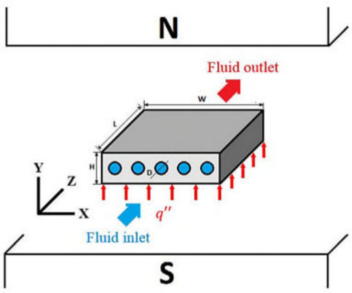


Fig. 1: System of 3D simulations for validation

The 3D model for finite element simulation and the meshing are shown in Fig. 2. The model was then imported to ANSYS Workbench for meshing and the number of meshing element is 6,856,920. The mesh file was then imported to ANSYS Fluent to set up the cases for simulation. The laminar model was chosen for viscous model. The properties of the ferrofluid were calculated using the equations described above. The boundary conditions were set as follows. A uniform heat flux of 66,000 W/m^2 was applied to the bottom surface. A uniform velocity inlet was applied to the tubes. The system was assumed to be steady state, homogeneous, laminar flow, A laminar model was chosen for the viscous model. Different materials were chosen and assigned to each layer. A heat generation of $q_{cell} = 3 \times 10^9 W/m^3$ was applied to the cell as thermal boundary condition. The inlet type was set as mass flow inlet with different values for comparison with further experiments. The interfaces were set as thermal coupled walls.

III. METHODS

A. *Magnetic field simulation*

According to Maxwell's equation, for nonconducting fluid the equation can be written as:

$$\bigtriangledown \cdot B = 0 \tag{1}$$

$$\bigtriangledown \times H = 0 \tag{2}$$

in which B is the magnetic flux density, H is the magnetic field intensity.B,H and magnetization M can be related as [11]

$$B = \mu_0(M + H) \tag{3}$$

In this study, the magnetic field effect is incorporated in the numerical simulations by adding the magnetic force source term to the momentum equation. The magnetic force can be calculated as [12]

$$F_M = (M \cdot \bigtriangledown)B \tag{4}$$

Thus, magnetic force F_M can be obtained as:

$$F_M = \frac{1}{2}\mu_0\chi_m(1+\chi_m)\bigtriangledown(H \cdot H) + \mu_0\chi_m H((H \cdot \bigtriangledown)\chi_m) \tag{5}$$

where χ_m is the magnetic susceptibility

B. *Theoretical analysis of CPV/T system*

The concentrated solar irradiance G on the top surface of the cell can be computed as [13]

$$G = CR \times DNI \tag{6}$$

in which CR is the concentration ratio and DNI is the direct normal irradiance. In this study, a concentration ratio of CR=1000 suns (1 sun = 1,000 W/m^2) was applied to the system. The heat generated by the cell can be expressed as:

$$q_{cell} = \frac{(1-\eta_{cell}) \cdot G \cdot \alpha_{cell} \cdot A_{cell}}{V_{cell}} \tag{7}$$

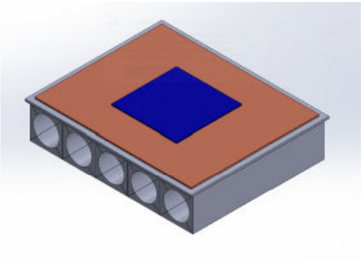
in whichA_{cell} and V_{cell} are the top surface area and volume of the cell, $alpha_{cell}$ is the Germanium absorptivity. η_{cell} is the electrical efficiency of the cell, which can be obtained as [14]

$$\eta_{cell} = \eta_{ref} - [\beta_{therm}(T_{cell} - T_{ref})] \tag{8}$$

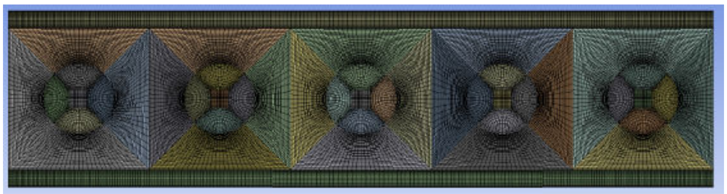
where η_{ref} is the reference electrical efficiency, β_{therm} is the thermal coefficient, T_{cell} and T_{ref} are the cell temperature and reference temperature. When the reference temperature T_{ref}=25°C (298K) and CR=1000 suns, the reference efficiency η_{ref}=40.3%. For Germanium the thermal coefficient β_{therm}=0.047% [15].

IV. RESULTS AND DISCUSSION

The contours of the system and the cell were generated by ANSYS Fluent. The temperature contours of the system at flow rate of 300 g/min with different magnetic flux densities are shown in Fig.3. The range of temperature was set as the same in each contour for comparison. As shown in the figure, when there is no external magnetic field applied, the heat is uniformly distributed. The laminar flow generates a thermal barrier on the interface of the pipe and the heating source, which significantly reduces the heat exchange efficiency. However, when an external magnetic field with B=800 and B=1600 is applied, the overall temperature of the heating source is reduced. More importantly, it is obvious that the thermal barrier is broken, and the laminar flow is broken

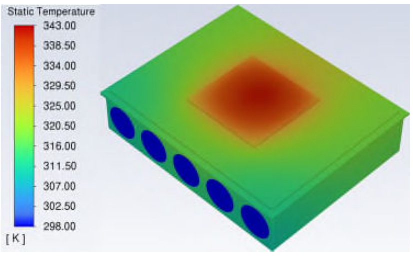


(a) 3D model of heat sink

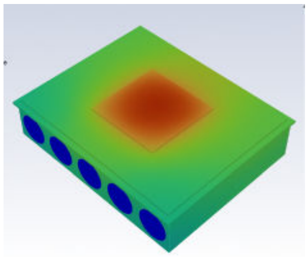


(b) Meshing results of 3D simulation

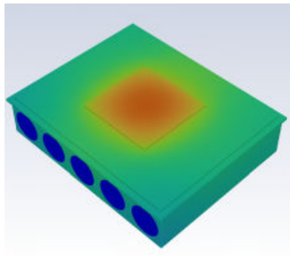
Fig. 2: 3D simulation model



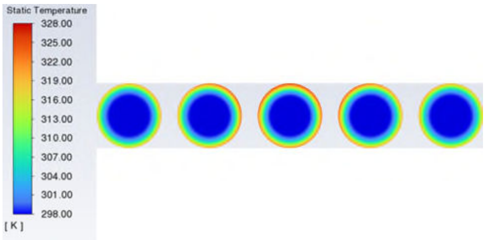
(a) B=0



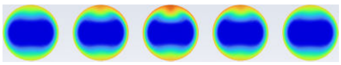
(b) B=800



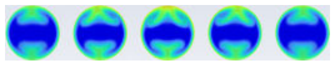
(c) B=1600



(d) B=0



(e) B=800



(f) B=1600

Fig. 3: Temperature under different magnetic field

into turbulence, as shown in Fig.3(b), 3(e), and 3(f), which improves the heat exchange efficiency and thus reduces the overall temperature of the system.

To explore the overall behavior of the cooling system, a series of simulations were carried out to show the influence of the external magnetic field on the cooling efficiency under different flow rates.

The results are shown in Fig.4. The curve at different flow rates all exhibited a reducing maximum cell temperature as the magnetic flux density increased. At a flow rate of 300 g/min, there was approximately a zero decrease in temperature from B=0 to B=400 G. However, from B=400 G to B=1600 G, the curve showed a sharp reduction from 340.2144 K to 335.1772 K. A similar trend can be found according to the curve at 450 g/min, but the reduction was more smooth (from 337.6750 K to 334.6670 K). At 600 g/min and 750 g/min, the maximum temperature remained approximately the same from B=0 to B=800 G. A smooth decrease was found from B=800 G to B=1600 G. Furthermore, at B=0, the initial maximum temperature varied from 341.6619 K to 334.4032 K. However, the four values were very close at B=1600 G. The value at

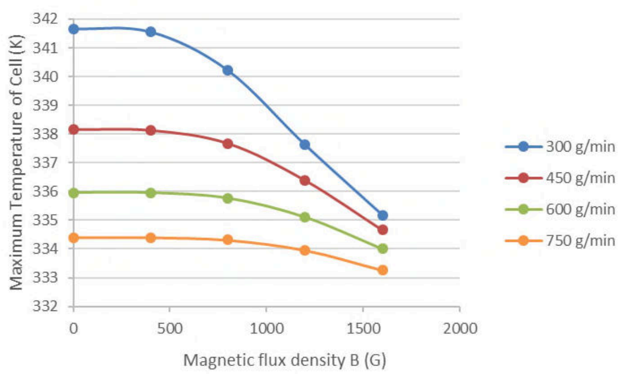


Fig. 4: Maximum cell temperature vs. Magnetic flux density curves

lower flow rate became approaching to the value at higher flow rate as the magnetic flux density increased. The results show that the proposed method can significantly improve the cooling efficiency, especially as lower flow rate system. This is a passive way of improving cooling efficiency which is easy to implement and energy efficient.

In design considerations of practical cooling systems, the difference between the maximum and minimum cell temperatures, the so-called temperature non-uniformity of cell, is one of the main terms to be considered. Thus the cell temperature non-uniformity against magnetic flux density at different flow rate is shown and shown in Fig. 5. As is shown in the figure, at B=0 the curve with higher flow rate had relatively lower temperature non-uniformity. When the magnetic flux increased, the temperature non-uniformity showed different levels of reduction. The curve at 300 g/min showed the major decrease from 15.32 K to 13.81 K, followed by the curve at 450 g/min (from 15.41 K to 14.33 K). The decrease of temperature non-uniformity at 600 g/min and 750 g/min is smoother. This is because with the increasing of the flow rate, the major factor that influence the temperature of the system becomes flow rate rather than the fixed magnetic force. Furthermore, at B=0 the temperature non-uniformity was relatively close to each other. With the increase of the magnetic field, at about B=800 G the four systems show approximately the same values of temperature uniformity. After B=800 G, the temperature non-uniformity at 300 g/min stared to be lower than other three curves. Similar change also happened at B=1200 G. At B=1600 G, the curve with 300 g/min had the lowest temperature non-uniformity which is far lower than other three curves. The curve with 450 g/min showed relatively lower temperature non-uniformity. The curves of 600 g/min and 750 g/min remains relatively high temperature uniformity. The results show that the temperature uniformity of the system can be influenced by the external magnetic field. With increasing the magnetic field, the uniformity of the system is decreased. However, with higher flow rate, the system shows a tends to remain the temperature uniformity at a higher level.

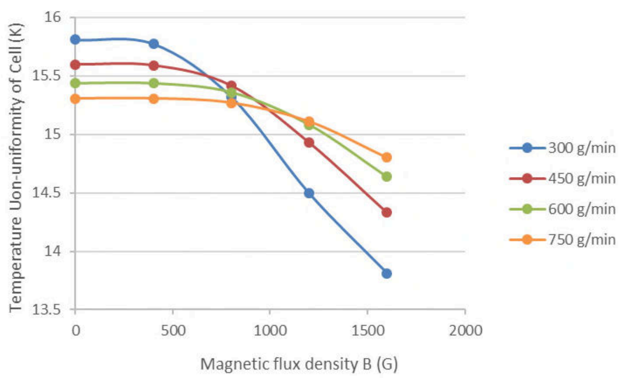


Fig. 5: Cell temperature non-uniformity vs, Magnetic flux density curves

In addition to the efficiency of the cooling system, the impact that the cooling system brings to overall system performance should also be investigated. The electrical efficiency of the cell vs. magnetic flux density curves at different flow rate were drawn and shown in Fig. 6. As shown in the figure, at B=0 all the curves showed a relatively lower electrical efficiency value. As the magnetic flux density grew, the curves showed different levels of efficiency improvement. The improvement of the curve at 300 g/min was the greatest, followed by the curve at 450 g/min. A sharp increase of efficiency can be observed from B=400 G to B=1600 G. The curves at 600 g/min and 750 g/min showed relatively more smooth improvement of efficiency. Furthermore, at B=0 the initial electrical efficiency in different curves varied greatly from 38.99% to 39.31%. However, when the magnetic flux density reached B=1600 G, the values were very close to each other, especially the curves at 300 g/min and 450 g/min. The results show that when applying a stronger external magnetic field, the electrical efficiency of the system is increasing, especially when the flow rate is at lower level.

The results indicates that the cooling efficiency of the system can be improved by changing the strength of the external magnetic field. According to the maximum temperature curve shown in Fig. 4, such pattern of efficiency enhancement can be stronger with a lower flow rate. Meanwhile, the trend of the curve illustrates that there is a potential value of magnetic flux density that the efficiency of the cooling systems with lower flow rates can even be higher than those with higher flow rates. For example, in current study the efficiency of system at 300 g/min can probably surpass the systems at 450 g/min and 600 g/min. Since the magnetic field is generated by permanent magnets which do not cost extra energy to maintain the field, the results show a possibility that the cooling system using ferrofluid as coolant can achieve higher efficiency with lower cost of energy.

According to the results of the velocity and temperature distribution of the outlet, it can be found that with the impact of the external magnetic field, both the temperature and velocity distributions in the tube. This is because the motion of magnetite nanoparticles was influenced by the magnetic force. Due to the direction of magnetic field and temperature, the magnetic force applied on the ferrofluid near both side walls always pointed to the center of the tube. Therefore, the thickness of the boundary layer with higher temperature was reduced and eventually gathered on the top and bottom walls of the tubes. These also indicate the mechanism of how the flow velocity was higher on both sides than top and bottom. In the light of non-uniformity of temperature and velocity, the convective heat exchange was enhanced and eventually lead to the improvement of cooling efficiency. The results of the cell temperature non-uniformity indicate that with a stronger magnetic field, the temperature uniformity can be improved, especially at a lower flow rate. As shown in Fig. 5, the case at 300 g/min with magnetic flux density of B=1600 G. Such findings indicated that with the cooling system using ferrofluid as coolant, there can be better temperature uniformity of the CPV system. When the efficiency of the cooling system gets higher, the uniformity of the system can be maintained in a relatively stable level or even be improved. This can effectively help the system especially the cell avoid hot spot, which can improve the performance and the lifetime of the system. The curves of electrical efficiency showed different levels of increase of cell electrical efficiency with stronger external magnetic field. The result indicates that the cooling system using ferrofluid as coolant improves not only the cooling efficiency of the CPV/T system but also the performance of the system. Furthermore, there is a potential trend that with an external magnetic field, if it is strong enough, better system performance can be achieved even in a low flow rate.

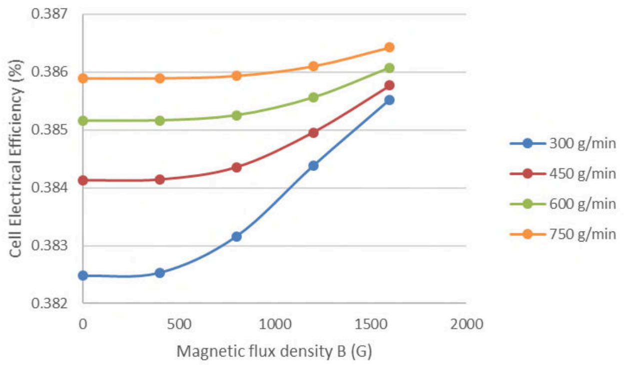


Fig. 6: Cell electrical efficiency vs. Magnetic flux density curves

V. Conclusion

In this study, a novel dynamic cooling system using ferrofluid as coolant was designed and investigated. Simulations were performed to evaluate the efficiency and performance of the system. The results show that the proposed method can passively break the laminar flow into turbulence and thus enhance the heat exchanging efficiency in a cost effective manner. In addition, due to the nano-scale nature of ferrofluid, the current approach can be used to build micro-scale or nano-scale cooling systems, where potentially more engineering and medical applications can be explored. Future work will focus on the implementation of the proposed cooling method.

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