Heat pipes as a passive cooling system for flywheel energy storage application

A P Tetuko1,*, R K Hadi1, M Faqih2, E A Setiadi1, C Kurniawan1 and P Sebayang1

1Research Center for Physics, Indonesian Institute of Sciences (LIPI), Bld. 440-442 Puspiptek Office Area, Tangerang Selatan, Banten, Indonesia
2Department of Mechanical Engineering, Faculty of Engineering, University of Pamulang, Jalan Surya Kencana, Pamulang, Banten, Indonesia

*E-mail: anggito.pringgo.tetuko@lipi.go.id

Abstract. In this research, the effects of the heat pipes arrangement as a passive cooling system in an electric motor for the flywheel energy storage application were analysed. Two heat pipes variations were used and attached to the outer surface of the electric motor, 4 and 6 heat pipes arrangements, respectively. The test was also compared with the condition where no heat pipes attached. A numerical model was developed to simulate the temperature distribution on the electric motor. An analytical model was also used to calculate the effect of the fin length to the heat transfer capability of the heat pipes. The test result suggested that the heat pipes can be used as a passive cooling system and could reduce the temperature on the surface of the electric motor significantly. The arrangement with 6 heat pipes has the highest temperature reduction from 50 to 35°C as compared to other conditions. The numerical simulation has a good agreement with the experimental results conducted in the laboratory and was used as validations for the model. The analytical model suggested that the increase of the fin length in one heat pipe affects the heat transfer surface area and thus the heat dissipation can be enhanced.

1. Introduction

There are several problems that occur in the power plant operation, such as power failures, fuel refueling, and system maintenances [1]. In order to resolve these problems, an energy storage system needs to be developed. An energy storage system can be used as an additional power source during an unstable condition. Flywheel energy system works by rotating a mass based on the inertia mechanism and store the mechanical energy to be used when the main power sources stop [2-4].

An electric motor can be used as the initial energy to turn the flywheel energy system. However, over-heating could occur in the electric motor and will decrease its performance [5-7]. Thus, a cooling system is required to reduce the operating temperature of the electric motor [8]. There are several types of cooling system that can be used in the electric motor (active and passive methods). The heat pipes as a passive cooling system offer several advantages, such as: simple, high heat dissipation rate, low maintenance cost and can be used in different arrangements and orientations [9-11].

In this study, the heat pipes cooling system arrangements were tested to analyse the temperature distribution on the outer surface of the electric motor in the flywheel energy storage system.
Experimental results were later used to validate the numerical model developed using a SimScale software. An analytical model was also developed to calculate the effect of fin length in one heat pipe to the heat transfer capability for both convection heat transfer methods (forced and natural).

2. Experimental Methods

The passive cooling system with different arrangements (4 and 6 heat pipes) was attached to the surface of the electric motor and was cooled using forced convection (e.g. blower) as presented in figure 1 (a). Several thermocouples (connected to a data logger and a computer) were attached to the surface of an electric motor to monitor their temperatures. As a comparison to the experimental test, a numerical model was developed to simulate the temperature distribution on the electric motor as shown in figure 1 (b).

In the analytical model, some parameters are needed for analysing the heat pipe system capability (the effect of fin length) to dissipate the heat in the electric motor using both forced and natural convection. The equations used in the analytical model are shown below [12, 13].

\[
Ra = \frac{g \beta (T_s - T_a) L_c}{\nu^2} \text{ Pr} \tag{1}
\]

\[
Nu = 0.54 Ra^{1/4} \tag{2}
\]

\[
Nu = 0.664 \cdot \text{Re}^{0.5} \text{ Pr}^{0.3} \tag{3}
\]

\[
h_{\text{air}} = \frac{Nu \cdot K_{\text{air}}}{L_c} \tag{4}
\]

where \(Ra\) is the Rayleigh number, \(g\) is the gravity (9.8 m/s\(^2\)), \(\beta\) is the coefficient of thermal expansion (K\(^{-1}\)), \(\nu\) is the kinematic viscosity (m\(^2\)/s), \(\text{Re}\) is the Reynolds number, \(T_s\) and \(T_a\) are the surface and the ambient temperatures (\(^\circ\)C), \(Nu\) is the Nusselt number, \(\text{Pr}\) is the Prandtl number, \(h\) is the coefficient of convection of the air (W/m\(^2\) \(^\circ\)C), \(K_{\text{air}}\) is the thermal conductivity of air (W/m. \(^\circ\)C), \(L_c\) is the fin length (m).

3. Results and Discussion

The results from the experiment and the numerical model are shown in figures 2 (a) and (b) and suggested that the heat pipes attached to the surface of the electric motor can dissipate the heat. Figure
2 (a) shows that the surface temperature of the electric motor decreases from 50 to \(45^\circ C\) at the maximum temperature by attaching 4 heat pipes. On the other hand, the use of 6 heat pipes can significantly reduce the temperature of the surface up to \(15^\circ C\) (from 50 to \(35^\circ C\)) at the maximum level. Based on the graph as well, it can be concluded that there is a non-linear reduction after the temperature reaching a maximum value, particularly between 400 to 500 s in both arrangements (4 and 6 heat pipes) caused by the blower at the condenser section of the heat pipes that dissipate the heat from its evaporator section. Another reason is caused by the flywheel rotation (that stored the kinetic energy) and continue to decrease as the time increased and affected the heat generated by the electric motor. The attachment of heat pipes in both arrangements reduces the maximum temperature on the surface of the electric motor as presented in figure 2 (a).

The temperature contour as a result of the numerical model confirmed that uniform temperature distributions can be achieved by attaching the heat pipes to the electric motor and reached the maximum temperature of \(50^\circ C\), similar as in the experimental results as validations. The attachment of heat pipes suggested a similar temperature reduction trendline on the surface of the electric motor as conducted by Putra and Ariantara [5].

The Reynolds number as a function of the fin length on the forced convection method is shown in figure 3 (a) and suggested that the increase of the fin length enhance the Reynolds number. As presented in figure 3 (b), there is a difference in the heat dissipation capability between the forced and natural convection that caused by the air velocity and affects the coefficient of convection. In the natural convection, the air movement occurs as a result of the temperature changes that have an impact on the fluid density. On the other hand, the velocity movement in the forced convection is affected by a mechanical device (e.g. blower). By using the forced convection method, the heat can easily be removed and dissipated from the surface of the electric motor through the heat pipes condenser section using a blower (where the fins arrangement attached). Previous research conducted by Tetuko et.al, 2016 [14] and Tetuko et.al, 2018 [10, 15] for proton exchange membrane (PEM) fuelcell applications also confirmed the capability of heat pipes to effectively remove the heat for maintaining the optimum temperature condition.

The effect of the fin length attached to the condenser section of the heat pipes to the Nusselt number and the coefficient of convection are presented in figures 4 (a) and (b). The results indicated that the increase of the fin length attached to the condenser section of the heat pipes increased the Nusselt number affected by the increase of the Reynolds number (forced convection) and the Rayleigh
number (natural convection). However, the coefficient of convection decreased by increasing the fin length as suggested by equation 4. Both of the results in figures 4 (a) and (b) suggested that the forced convection method has a better performance compared to the natural convection method.

Heat dissipated by the heat pipes and their thermal resistance using both forced and natural convection is shown in table 1. The result shows that the decrease in the total thermal resistance increase the heat dissipation capability of the heat pipes. In the heat pipes arrangement to be used as a passive cooling system, the overall thermal resistance affects the heat dissipation capability as suggested by Wang [16], Lin and Wong [17], and Tharayil et.al [18].

![Figure 3.](image1.png)  
**Figure 3.** (a) Reynolds number as a function of the fin length (b) Heat dissipation as a function of the fin length.

![Figure 4.](image2.png)  
**Figure 4.** (a) Nusselt number as a function of the fin length. (b) The coefficient of convection as a function of the fin length.
4. Conclusions
The use of heat pipes can significantly reduce the surface temperature of the electric motor from 50 to 35 °C at the maximum level (by using 6 heat pipes arrangement), particularly using the forced convection method. This temperature reduction can maintain the optimum working temperature (e.g. at low temperature, 25-30°C) on the electric motor as an initial energy input to turn the flywheel to be used as the mechanical energy storage. Another parameter that affects the heat dissipation by the heat pipes in the current cooling system arrangement is the fin properties (e.g. the fin length) attached to the condenser section of the heat pipes. The heat pipes types (e.g. orientation, pressed thickness and thermal resistance) that have been chosen to be used as the passive cooling system play an important role in achieving uniform and optimum temperature distribution.

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References
[1] Stoppato A, Mirandola A, Meneghetti G and Casto E L 2011 Energy 37 228
[2] Amiryar M E and Pullen K R 2017 Applied Sciences 7 286
[3] Parfomak P W 2012 Congressional Research Service Tech Rep R. 2012 146
[4] Huff G 2013 Report SAND 2013
[5] Putra N and Arianata B 2017 Appl. Therm. Eng. 126 1156
[6] Jahic A, Hederic Z and Atic M 2015 International Journal of Electrical and Computer Engineering Systems 6 (1) 15
[7] Kuria J and Hwang P 2011 International Journal of Mechanical Engineering 11 1
[8] Lim D H, Lee M, Lee H and Kim S C 2014 Energies 7 961
[9] Sabbah R, Kizilel R, Selman J R and Al-Hallaj S 2008 J. Power Sources. 182 630
[10] Tetuko A P, Shabani B, and Andrews J 2018 Energies 11 1
[11] Faghi J 2014 Front Heat Pipes 5 1
[12] Holman J P 2010 Heat Transfer (Mc Graw Hill)
[13] Cengel Y 2003 Heat Transfer: A Practical Approach (Mc Graw-Hill)
[14] Tetuko A P, Shabani B and Andrews 2016 Int. J. Hydrogen Energy 41 4264
[15] Tetuko A P, Shabani A P, Omrani R, Paul B and Andrews J 2018 J. Power Sources 397 177
[16] Wang J C 2011 Int. J. Therm. Sci 50 97
[17] Lin K T and Wong S C 2013 Appl. Therm. Eng 50 46
[18] Tharayil T, Asirvatham L G, Cassie C F M and Wongwises S 2017 Appl. Therm. Eng 122 685