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Thermal Analysis of Radial Piezoelectric-Magnetic Fan (RPMF) for Electronics Cooling

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Abstract: Application of piezoelectric fan in electronic cooling system has been proven that it is more efficient than natural convection with least power consumption and has high potential to replace existing rotary fan for its simplicity and longer life. An integration of piezoelectric fan with magnet is to widen the cooling coverage area with similar power consumption and cost of running a single piezoelectric fan. By optimizing the repulsive magnetic force generated in between the magnets, the overall fans oscillate with significant average amplitude. The purpose of this paper is to investigate the performance of multiple piezoelectric-magnetic fan and its significance in reducing temperature while enhance the heat transfer. The parameters under investigation are the distance between magnets and fans orientation. In this study four magnetic fans were activated by a piezoelectric fan. It is found that at distance between magnets is 14 millimeters; the average amplitude is largest at highest resonant frequency. The multiple fans is better to be arranged in radial orientation for its ability to produce larger repulsive magnetic force to oscillate the adjacent fans. The distribution of repulsive magnetic force in radial orientation is five times better than array orientation. Therefore, radial piezoelectric-magnetic fan (RPMF) produces larger average amplitude of fans which is 111%. 30% of power consumption per unit coverage area is secured. RPMF generates average wind velocity of 0.4m/s compared to array orientation 0.17m/s.

Keywords: piezoelectric fan, radial orientation, amplitude, magnetic fan.

1. Introduction

An electronic device must be accompanied with a good cooling system to ensure the durability and reliability of a device is at acceptable range. Continuous exploration on piezoelectric fan as alternative air cooling system for electronic devices proves that air is still relevant as cooling medium nowadays. Technically, a piezoelectric fan converts electrical energy to mechanical energy (oscillation) to disrupt the air flow around the tip of the fan. there are many advantages of piezoelectric fan such as it capable to demolished electromagnetic noise generated by the motor in normal rotary fan (Kimber, Suzuki, Kitsunai, Seki, & Garimella, 2009), low power consumption (below 100mW) (Ma & Li, 2015), longer life due to no usage of bearings (Shoemaker, 2011) and light in weight (Yoo, Hong, & Cao, 2000) since it is composed of a thin blade and simple circuit only.

Material selection of extended blade that attached to the piezoelectric actuator is very important as it influences the resonant frequency and amplitude of the fan (Kimber et al., 2009) in terms of stiffness and elasticity level of the blade. A good extended blade for a single piezoelectric fan is where the fan able to execute largest amplitude at highest resonant frequency. At the same time, the amplitude of the fan has acceptable stiffness and elasticity therefore able to remove the hot air from the electronic device and reduce the temperature. Mylar has been used as extended blade (Ma & Li, 2015)(Shoemaker, 2011) for its promising results in enhancing the performance of the piezoelectric fan. Other materials that were used as extended blade are aluminum alloy, phosphor bronze and brass (Shyu & Syu, 2014) and carbon fiber

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(Yu et al., 2014). The dimension of the fan also plays important role in determining the performance of the piezoelectric fan (Yoo et al., 2000). The increment of length of the fan influences more on the maximum amplitude whereas lowers the resonant frequency. However, the main target in cooling system is to get larger Reynolds number which proportional with the wind velocity generated by the fan. Therefore, the amount of amplitude at optimum resonant frequency should be obtained. From other side, the orientation of the fan with respect to the heat source (Jeng & Liu, 2015) also varies the amount of air flow to the heated surface. Jeng & Liu (2015) studied on transverse and axial fan oscillation whose claimed that transverse oscillation gives more heat transfer whereas (Liu, Huang, Sheu, & Wang, 2009) whose studied on vertical and horizontal fan position found that vertical arrangement has higher effectiveness of heat rejection. However, the affected air between the fan and the heat source is quite small. Therefore, in order to widen the affected area, more fans should be used. Ma & Li (2015) has investigated the effect of magnet to the piezoelectric fan. The importance of location of magnet in piezoelectric fan has been discovered by (Fadhilah, Robiah, & Shamsul, 2018a) whose reporting on dual piezoelectric-magnetic fans.

In multiple fan orientation, high resonant frequency and amplitude are the most important parameters and the product of both parameters gives the velocity of air produced by the fan. An integrated piezoelectric-magnetic fan has been introduced by Ma, Su, & Luo (2013). In the system, only single piezoelectric fan has been used and other fans were activated by repulsive magnetic force. The magnets were placed in repulsive mode (S-S or N-N) so that the adjacent fan was mounted in such a way that they are pushing each other. This integration reduced the input power required to activate all the fans. Adding on single or dual magnets to the extended blade has increased the total weight of the fan thus reduces the resonant frequency of the fan. Lower resonant frequency indicates lesser oscillation in a second. Lesser oscillation cause less air to be removed away from the heat source. Multiple blades run by single piezoelectric fan also require optimum stiffness and elasticity of the extended blade so that more amplitude could be transferred to the adjacent fan.

However, the distribution of amplitude which depends on the repulsive magnetic force is not even. As the magnetic fans farther from the driving fan, the amplitude becomes smaller. (Fadhilah, Robiah, & Shamsul, 2018b) showed that radial orientation of piezoelectric-magnetic fans is better in transferring repulsive magnetic force to adjacent magnetic fans thus able to improve the cooling process in electronics devices. This paper is the extension of the study in thermal analysis particularly in cooling electronic devices.

2. Theoretical Analysis

Integrated piezoelectric fan and magnetic fans has shown that it is able to oscillate passive fans by supplying force from magnet. In this case, the magnets are arranged in same pole facing each other thus generate repulsive magnetic force. The performance of multiple piezoelectric-magnetic fans will be calculated theoretically and validated experimentally. The parameters under investigation that affecting the performance of RPMF are the location of magnets, distance between magnets and orientation of the multiple piezoelectric-magnetic fans. The best design is selected by looking at the air velocity generated. Thermal analysis is conducted based on the selected design parameters.

2.1 Mathematical Modeling

The oscillation of piezoelectric-magnetic fan is depending on the accumulated stiffness on each fan which will determine the force required to oscillate the fan. The stiffness of a fan is depending on the fan blade itself and the magnet attached to it. Stiffness increases if number of magnet increase. The strength of a piezoelectric fan is depends on the supply voltage to it. The bending force from piezoelectric actuator can be found from (Yoo et al., 2000):

$$F=\frac{3wtd_{31}VE}{2L} \tag{1}$$

where w, t, and L is width, thickness, length of piezoelectric actuator. d_{31}, V and E is the piezoelectric strain coefficient of the material, supply voltage and Young modulus of the ceramic respectively. The bending force oscillates the piezoelectric actuator slightly and the fan amplitude increases as material with smaller young modulus attached to the actuator. In this study, Mylar will be used as it produces high fan amplitude. Mylar bends the piezoelectric actuator and extended blade at same frequency. Amplitude gained by different material attached to the piezoelectric actuator can be calculated as:

$$A=\frac{FL^3}{3EI} \tag{2}$$

$$f_r=\frac{\alpha_n^2}{2\pi}\sqrt{\frac{EI}{mL^4}} \tag{3}$$

where α_n is 1.875 for first mode frequency. Combining eq.2 and eq 3 gives a relationship between resonant frequency and amplitude.

$$f_r = \frac{\alpha_n^2}{2\pi}\sqrt{\frac{F}{3mLA}} \quad (4)$$

Adding on a magnet to the extended blade will increase the force required to oscillate the fan due to additional weight and magnetic force to actuate the adjacent passive fans. The magnetic force between two cylindrical magnets in radial orientation can be calculated as:

$$F_m(x) = \left[\frac{B_0^2 A_m^2 (t_m^2 + r_m^2)}{\pi \mu_0 t_m^2}\right]\left[\frac{1}{x'^2} + \frac{1}{(x'+2t_m)^2} - \frac{2}{(x'+t_m)^2}\right] \quad (5)$$

where B_0, A_m, t_m, r_m, μ_0 and x' are the magnetic flux density, surface area, thickness and radius of the magnet, permeability of the intervening medium and distance between two magnets respectively.

$$x' = \frac{x}{b}(l' + b) \quad (6)$$

where $b = \frac{x}{2sin\theta}$. The schematic diagram is shown in Fig. 1. In radial orientation, the distance between magnets is slightly different compare to distance between magnets in array orientation which gives more amplitude to adjacent passive fans in radial orientation. Each magnetic fan receives different total accumulative bending force thus results in different individual amplitude.

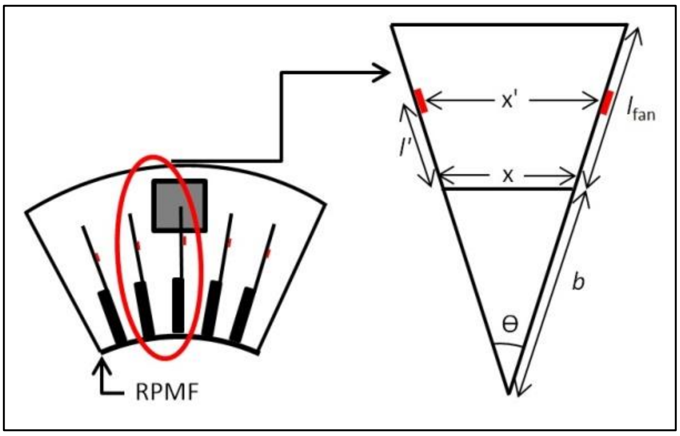


Fig.1 Schematic diagram of repulsive magnetic force between adjacent magnets

In RPMF arrangement, the fan does not necessarily running at resonant frequency. The fan is running at a frequency in such a way that the amplitude generated is at maximum average value among the fans. Air flow can be calculated from the given equation:

$$\vartheta = fA \quad (7)$$

A. Thermal Analysis

The average heat convection coefficient can be calculated once the thermal power to heat up the heat source Q_{heat} is known. According to the one-dimensional Fourier's Law, the thermal power can be derived from equation below:

$$Q_{heat} = -k\left(\frac{\pi d^2}{4}\right)\left(\frac{dT}{dx}\right) \quad (8)$$

Therefore, the average heat convection coefficient can be found using below equation:

$$h = \frac{Q_{heat}}{\bar{A}(T_s - T_a)} \quad (9)$$

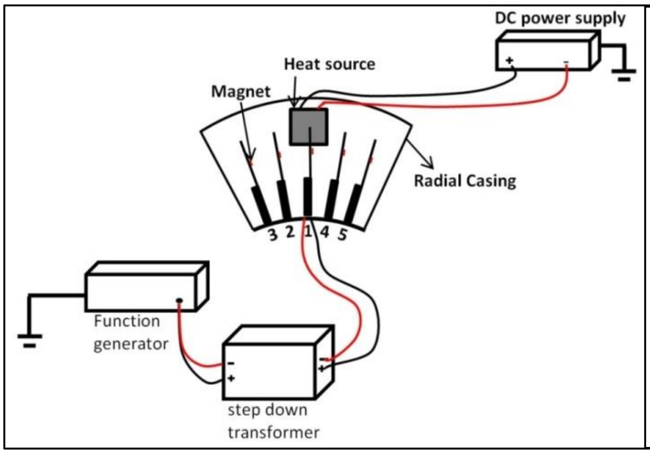
where $\bar{A}$ is the total surface area. T_s and T_a is average surface temperature of heat source and ambient temperature respectively. Thermal resistance and Reynolds number of the RPMF can be calculated by:

$$R = \frac{T_s - T_a}{Q_{heat}} \tag{10}$$

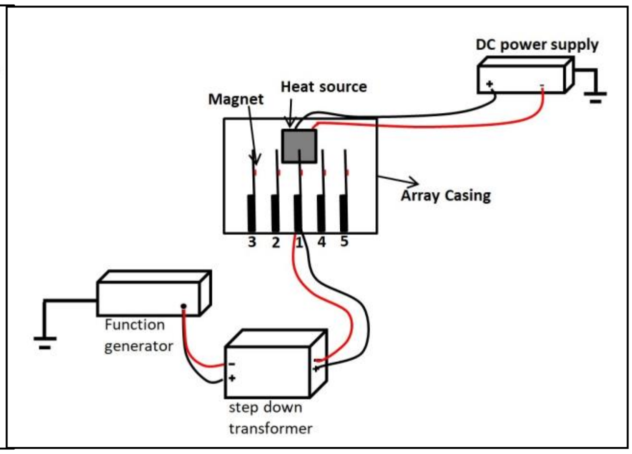
$$Re = \frac{VL_{RPMF}}{v_{air}} = \frac{fAL_{RPMF}}{v_{air}} \tag{11}$$

2.2 Experimental Setup

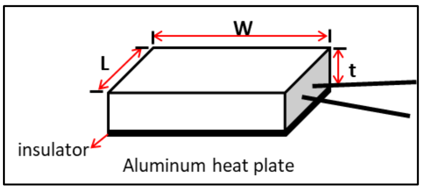
The schematic view of RPMF is elaborated in Fig. 2(a). The piezoelectric fan which was bought from (“Fans & resonators 65,” 2011) is labeled as fan no. 1. The piezoelectric fan was activated by connecting it to a step down transformer and a function generator. Magnets were placed on the extended blade as in (Fadhilah, Robiah, & Shamsul, 2017) as it gives more amplitude at same power input. Another 4 passive fans which driven by repulsive magnetic force were placed adjacent to the piezoelectric fan in a few distances. A dummy heat source with dimension (0.03 x 0.03 x 0.003)m were fabricated and placed in vertical arrangement as described in (Liu et al., 2009). The heat source was powered by DC power supply (Fig. 2(ii)).



(a)



(b)



(c)

Fig. 2 (a) Schematic diagram of RPMF, (b) Schematic diagram of Array piezoelectric-magnetic fan, (c) Dummy heat source

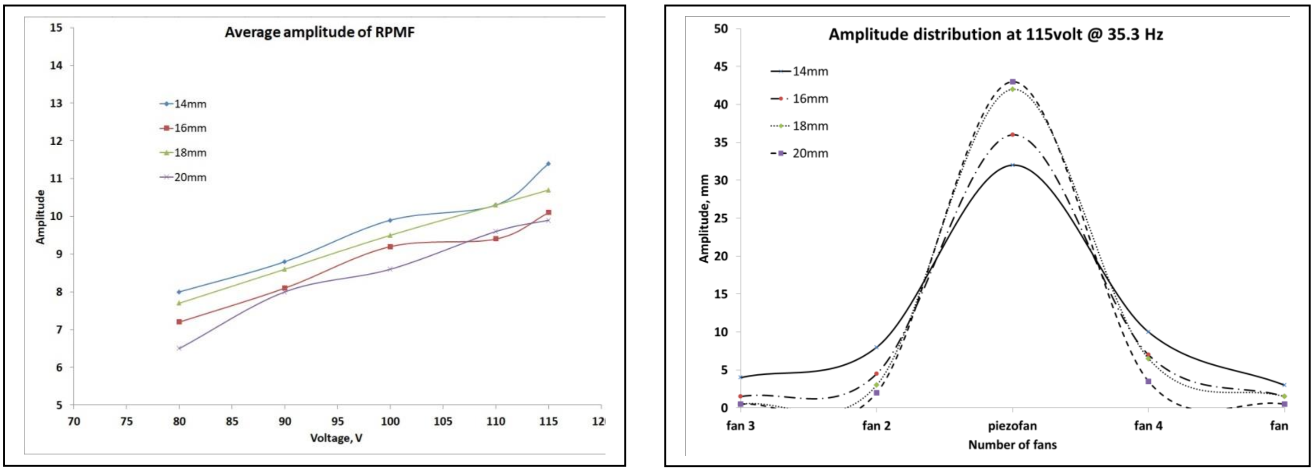
The performance of the RPMF was tested with single magnet on each fan and located in the middle of the extended blade (Fadhilah et al., 2017). The system was running at different input voltage. The amplitude of each fans were recorded before selecting the best amplitude and running frequency for thermal analysis. In thermal analysis, the RPMF was tested with different heat flux and the performance of RPMF was recorded. The driving piezoelectric fan was bought from (“Fans & resonators 65,” 2011) and the specification of the fan is listed in Table 1.

Table 1 Specification of piezoelectric fan ("Fans & resonators 65," 2011)

Item	Description	Item	Description
Input voltage	115 VAC, 60Hz	Capacitance	15nF
Power consumption	30mW	Volume flow rate	2CFM (0.9 l/s)
Peak air velocity	400FPM, (2.0 m/s)	Weight	2.8 grams
Mounting	#2-56 clr holes, 2 places	Temperature range	-20°C to 70°C
Dimension (actuator)	(64 x 12.7 x 0.15)mm	Dimension (extended blade)	(37 x 12.7 x 0.254)mm

3. Result and Discussion

As the input voltage increases, the piezoelectric fan is running stronger as shown in Fig. 3. At closer distance between magnets, greater repulsive magnetic force can be transferred to the adjacent fans thus initiate the oscillation of the magnetic fans. This is supporting what has been reported by (Ma et al., 2013).



(a) (b)

Fig. 3 (a) Average amplitude of RPMF at various input voltage and (b) Amplitude distribution of RPMF at 115VAC, 35.3Hz

The amplitude for each fan has been recorded in Table 2. From the results, the distribution of fan amplitude is not uniform and the gap between adjacent fans is quite large as shown in Fig. 4.

Table 2 Amplitude of each fan at different distance between fans

Distance between fans, mm	Amplitude, mm				
	Piezo fan(1)	Fan (2)	Fan (3)	Fan (4)	Fan (5)
14	32	8	4	10	3
16	36	4.5	1.5	7	1.5
18	42	3	0.5	6.5	1.5
20	43	2	0.5	3.5	0.5

The inconsistent amplitude distribution to the adjacent fans is due to inconsistencies of decrement in repulsive magnetic force as it is placed farther away from driving fan. The repulsive magnetic force acting on fan 3 and fan 4 is smaller compare to fan 2 and 4. The repulsive magnetic force in radial and array orientation is calculated theoretically. The result shows in Fig. 4 that radial orientation executed greater repulsive magnetic force compared to array orientation. For distance between magnet, x in between 5mm to 10mm, the reduction of force is too sharp, also representing the force is too large for both adjacent fans causing the fans to oscillate with much less amplitude. For x value in between 10mm to 15mm, the distribution of force is more balance between adjacent fans. In order to get higher average fan amplitude, the gap between the passive fans should be smaller as it goes farther from the piezoelectric fan.

By calculating eq. 5 and 6, the force generated due to repulsive magnetic force shows that radial orientation is better in generating more magnetic force. According to Fig. 4, when the gap between the magnets is too close, the repulsive magnetic force applied on each fans is too high against the fans to oscillate in greater amplitude. As the gap between the magnets larger up to 15mm, the oscillation of piezoelectric fan and passive fans are more balance. When the gap expanded more, less oscillation is seen on the magnetic fan and larger amplitude generated by the piezoelectric fan alone. It shows that there is lesser impact from the repulsive magnetic force acting on the fans. Therefore, the best distance between magnets that should be applied is 14mm.

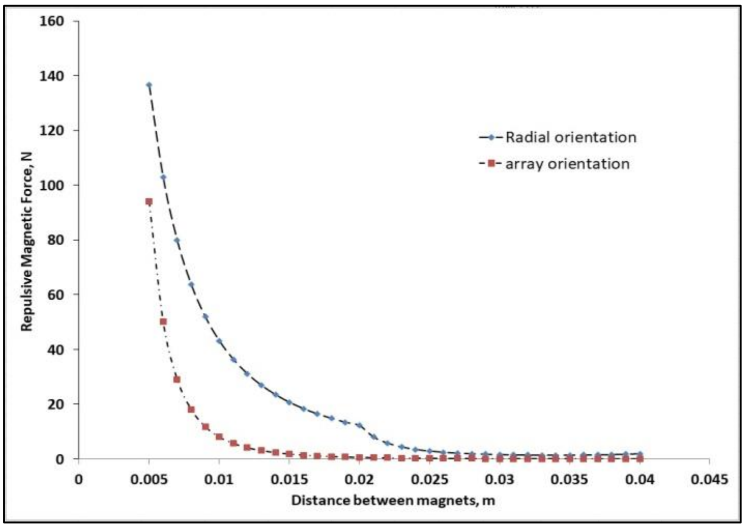


Fig. 4 Repulsive magnetic force in radial and array orientation.

By considering the best distance between magnets is 14mm, The RPMF was thermally investigated with different heat flux. Its shows that it able to increase the rate of cooling compare to natural convection thus enhances the average heat convection coefficient as shown in Fig. 5.

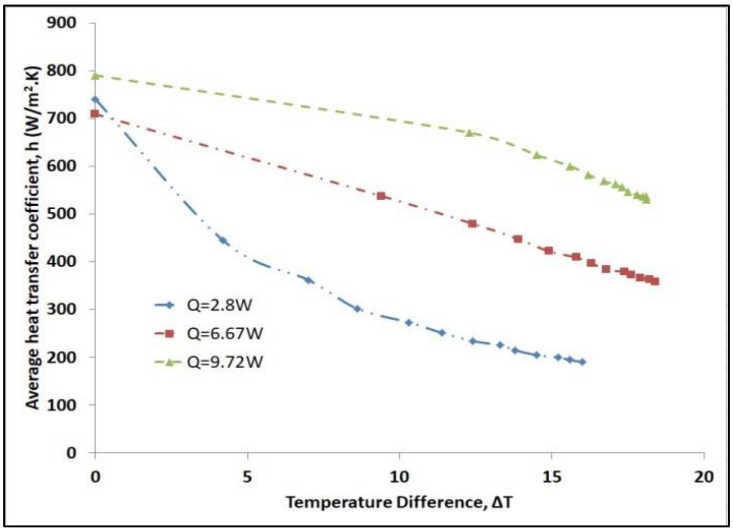


Fig. 5 Average heat convection coefficients at various heat flux.

The effectiveness of RPMF also can be seen from the reduction of thermal resistance as shown in Fig. 6. At the same time frame, initial and final temperature was recorded for different temperature on the heat source. From the experiment, RPMF able to reduce the temperature faster than natural convection thus proves that RPMF able to reduce the thermal resistance and the thermal efficiency can be improved by applying RPMF on the cooling system.

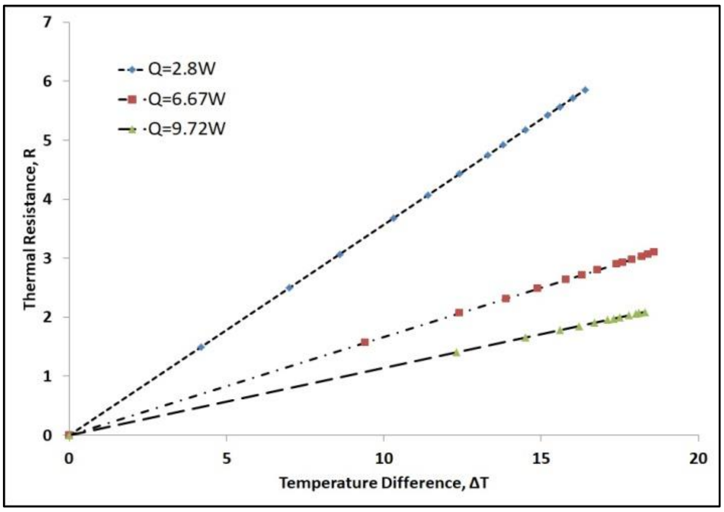


Fig. 6 Thermal Resistance of RPMF at various heat flux.

4. Conclusion

The integration of piezoelectric-magnetic fans in radial orientation (RPMF) proved that it able to enhance the cooling efficiency compared to natural convection and single piezoelectric fan. RPMF is clearly better than single piezoelectric fan in terms of coverage area. For same number of fans applied in different orientation, radial orientation has better coverage area compared to array orientation besides having better repulsive magnetic force generated between the magnets. In more specific, the advantages of RPMF are concluded as below:

- The best gap between fans is 14mm as it generates the best average amplitude thus producing air velocity at 0.39m/s.
- By considering similar distance between fans for array and radial orientation, the distance between magnets changes accordingly with respect to the angle of orientation, results to the distribution of repulsive magnetic force in radial orientation is five times better than array orientation.
- RPMF produces larger average amplitude of fans compared to array orientation which is 111%.
- RPMF secured 30% of power consumption per unit coverage area.
- RPMF generates average wind velocity of 0.4m/s compared to array orientation of 0.17m/s.

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