OPTIMIZATION OF MULTIPLE PIEZOELECTRIC MAGNETIC FANS FOR ELECTRONIC COOLING SYSTEM

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A thesis submitted in partial fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Razak Faculty of Technology and Informatics
Universiti Teknologi Malaysia

MAY 2020

DEDICATION

This thesis is dedicated firstly to my husband, Mohd Hazrol Shahril b. Hasan who always give full support for me to complete this thesis, not to forget my father and late mother who always advice to study up to the highest level that I can afford. To my parent in law, thank you for your understanding and moral support. Lastly, thank you to all my kids, Aisyah, Ameer, Adam and Ahmad for cheering me up and avoid me from stressful life. Always run for a success with love and patience.

ACKNOWLEDGEMENT

In the process of completing this thesis, I was dealing with many people, researchers, technicians, academicians, and practitioners. Their guidance, advices, knowledge sharing and motivation is much appreciated towards the preparation of this thesis. In particular, I would like to express my sincere gratefulness to my main supervisor, Associate Professor Dr. Robiah Ahmad, for understanding, encouragement, guidance, critics and friendship. I am also very thankful to my cosupervisor Associate Professor Dr. Shamsul Sarip for their assistance, advices and inspiration. Without their continued support and interest, I will not manage to complete this thesis.

I am also grateful to Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia (UTM) for funding my PhD study. A grant has been released for this study entitled for RM115k has helped a lot in preparing all the equipment for experimental study. Also thanks to the UTM staff for their assistance whenever is needed..

My fellow postgraduate members should also be acknowledged for their support. Their views, moral support and strength has motivated me to walk in this journey until the end.

ABSTRACT

Air cooling system for electronics is still preferable due to its simplicity and reliability. To date, some researches on air cooling showed that a piezoelectric fan is more efficient than natural convection with minimum power consumption. However, a single piezoelectric fan can only cover a small cooling area and more power might be consumed if multiple piezoelectric fans are applied. A multiple piezoelectric magnetic fan (MPMF) has proven to have a high potential to replace the existing rotary fan. Initially, the MPMF was designed in line/array (APMF). However, the deflection of the MPMF needs to be improved in fundamental analysis and validated by the experimental data from previous studies. Hence, the first objective of the study is to propose a new mathematical model for MPMF to include the location of magnet and distance between magnets to length ratio. A centripetal force is introduced as the contributing parameter to the equation of deflection of a radial piezoelectric magnetic fan (RPMF). The second objective is to optimize the multiple piezoelectric magnetic fan parameters using Response Surface Method (RSM). The experimental setup consisted of two divisions; parameters optimization and thermal analysis. The theoretical results of the fan deflection were compared with experimental data and the thermal performance of the proposed RPMF was compared with the benchmarked paper. The results showed that an optimal magnet location was on the Mylar blade, 44mm from the origin (63.8% of original length). The new location of magnet has led to increment of Reynolds Number to 924. The distance between magnets to length ratio is in the range of 14.5mm to 15.6mm (21%-22.6% of the fan length). By fixing the distance between magnets at 14.5mm, the resonant frequency and deflection of RPMF and APMF were 42.66Hz, 11.6mm and 40.68Hz, 9.4mm respectively. By varying the orientation of MPMF, the Reynolds number of RPMF was improved 32% compared to APMF. The heat convection coefficient increased by 8.07% to enhance the heat transfer performance by 8.06%. The thermal resistance reduced by 7.6% which led to 5% increment of overall thermal efficiency. In conclusion, the relocation of magnet has improved the overall performance of MPMF. The RPMF has been found to have a better cooling performance compared to APMF. Thus, RPMF has a high potential to be applied in electronics cooling system.

ABSTRAK

Sistem penyejukan udara untuk elektronik masih lebih baik kerana kesederhanaan dan kebolehpercayaannya. Setakat ini, beberapa penyelidikan dalam penyejukan udara menunjukkan bahawa kipas piezoelektrik lebih berkesan daripada perolakan semulajadi dengan penggunaan kuasa yang minimum. Walau bagaimanapun, kipas angin piezoelektrik tunggal hanya boleh merangkumi kawasan penyejukan yang kecil dan lebih banyak kuasa perlu digunakan jika beberapa kipas piezoelektrik digunakan. Oleh itu, kipas piezoelektrik berganda berserta magnet (MPMF) mempunyai potensi yang tinggi untuk menggantikan kipas yang sedia ada. Di peringkat awal rekabentuk, MPMF disusun dalam bentuk sejajar (APMF). Walau bagaimanapun, pesongan MPMF perlu diperbaiki secara teori dan disahkan oleh data eksperimen serta kajian terdahulu. Objektif pertama kajian ini adalah untuk mencadangkan pemodelan matematik baru bagi MPMF dengan memasukkan lokasi magnet, nisbah jarak antara magnet dan panjang kipas. Daya centripetal ditambah sebagai parameter yang menyumbang kepada jumlah pesongan kipas radial; RPMF. Objektif kedua adalah untuk meningkatkan kaedah pengoptimuman parameter bagi MPMF dengan menggunakan Kaedah Surface Response (RSM). Persediaan eksperimen terdiri daripada dua bahagian; pengoptimuman parameter dan analisis data haba. Hasil teori pesongan MPMF dibandingkan dengan data eksperimen dan juga kertas jurnal penanda aras. Prestasi APMF dan RPMF juga dibandingkan dengan kaedah yang sama. Keputusan menunjukkan bahawa lokasi magnet yang optimum berada di bilah Mylar, 44mm dari pemegang (63.8% panjang asal). Nisbah jarak antara magnet dan panjang bilah kipas ialah 14.5mm hingga 15.6mm (21% -22.6%). Dengan menetapkan jarak antara magnet pada 15.6mm, frekuensi resonant dan pesongan RPMF dan APMF masing-masing adalah 42.66Hz, 11.6mm dan 40.68Hz, 9.4mm. Dengan mempelbagaikan orientasi MPMF, bilangan Reynolds RPMF meningkat 32% berbanding dengan APMF. Keupayaan perolakan haba meningkat sebanyak 8.07% untuk meningkatkan prestasi pemindahan haba sebanyak 8.06%. Rintangan haba berkurang sebanyak 7.6% yang membawa kepada kenaikan 5% kecekapan haba keseluruhan. Sebagai kesimpulan, kedudukan magnet telah menambahbaik prestasi MPMF secara keseluruhan. RPMF pula terbukti mempunyai prestasi penyejukan yang lebih baik berbanding APMF. Oleh itu, RPMF mempunyai potensi tinggi untuk digunakan dalam sistem penyejukan elektronik.

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LIST OF ABBREVIATIONS

MEMS	-	Micro-electr0mechanical systems
DCJ	-	Dual-piezoelectric Cooling Jet
MPMF	-	Multiple Piezoelectric-Magnetic Fans
OFAT	-	One Factor at A Time
RSM	-	Response Surface Method
DoE	-	Design of Experiment
PZT	-	Plumbum Zirconate Titanate
XML	-	Extensible Markup Language
ANN	-	Artificial Neural Network
GA	-	Genetic Algorithm
PSO	-	Particle Swarm Optimization
PET	-	Polyethylene terephthalate
CCD	-	Central Composite Design
DAQ	-	Data acquisition
D-MFPA	-	Dual-sided Multiple fans with Piezoelectric Actuator
APMF	-	Array Piezoelectric-Magnetic Fans
RPMF	-	Radial Piezoelectric-magnetic Fans
SPF	-	Single Piezoelectric Fan
LED	-	Light Emitting Diode
PVC	-	Polyvinyl Chloride
DE	-	Design Expert
UTM		Universiti Teknologi Malaysia
ANOVA	-	Analysis of Variance
SMSS	-	Sum of squares sequential model
AC	-	Alternating current
NI	-	National Instrument

LIST OF SYMBOLS

V	-	Voltage	Volt
F	-	Force	N
dB	-	Desibel	-
d_{31}	-	Piezoelectric constant	C/N
E_{piezo}	-	Modulus elasticity of piezoelectric	Pa
E_{Mylar}		Modulus elasticity of Mylar	Pa
f_r	-	Resonant frequency	Hz
t	-	Thickness	mm
l	-	Total Length	mm
I	-	Moment of inertia	$kg.m^2$
H	-	Thickness of piezoelectric actuator	mm
L	-	Length of Piezoelectric actuator	mm
w	-	Width	mm
α_f	-	Fan orientation	θ
S_l	-	Length in horizontal axis	mm
S_h	-	Length in vertical axis	mm
Φ	-	Phase angle	θ
υ	-	Velocity	m/s
x	-	Location of magnet	mm
d	-	Distance between magnets to length ratio	-
r	-	Radius	mm
Re	-	Reynold Number	-
k_c	-	Thermal conductivity	W/(m.K)
m_{eff}	-	Effective mass	g
m_b	-	Mass of beam	g
m_{mag}	-	Mass of magnet	g
λ	-	wavelength	mm
k	-	Magnetic stiffness	N/m
F_{piezo}	-	Piezoelectric force	N
F_{mag}	-	Magnetic force	N

F_c	-	Centripetal force	N
d_2	-	Distance between fans	mm
b	-	Distance between origin to the piezoelectric actuator	mm
l'	-	Length of Mylar from initial to the magnet	mm
B_0	-	Magnetic flux density	Tesla
r_{mag}	-	Radius of magnet	mm
t_{mag}	-	Thickness of magnet	mm
π	-	Pi (3.1416)	-
μ_0	-	Permeability of intervening medium	H/m
k_{piezo}	-	Stiffness of piezoelectric fan	N/m
k_{mag}	-	Magnetic stiffness	N/m
ω_{piezo}	-	Angular frequency of piezo	Hz
m_{piezo}	-	Mass of piezoelectric fan	g
r	-	Radius of RPMF	mm
Q	-	Total heat transfer	Watt
Q_v	-	Convective heat transfer	Watt
Q_c	-	Conduction heat transfer	Watt
Q_r	-	Radiation heat transfer	Watt
A_c	-	Cross section area for conduction	m^2
T	-	Temperature	ºC
L_c	-	Distance between two point of temperature	m
h	-	Heat convection coefficient	$W/m^2.K$
A_h	-	Surface area of heat sink	m^2
R_{tot}	-	Thermal resistance	ºC/W
η	-	Thermal efficiency	%
M_{MPMF}	-	Dimensionless heat convection number	-
Re	-	Reynolds number	-
Pr	-	Prandtl number	-
Nu	-	Nusselt number	-
δ	-	Fan deflection	mm
L_f	-	Characteristic length of piezoelectric fan	-
v_a	-	Kinematic viscosity of air	m^2/s

W_m	-	Width of flexible blade	mm
A	-	Amplitude	mm
N	-	Number of fans	-
L_h	-	Length of heat source	m
c_p	-	Specific heat	kJ/kg.K
μ	-	Dynamic viscosity	$N.s/m^2$
α	-	Thermal diffusivity	m^2/s

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Nowadays, almost everything was run by electronic-based devices regardless of its size and applications, functioning for kids to adults and operating throughout the days or nights. The devices could be used nonstop by the users and if the heat dissipation system is not able to sustain, the high temperature might harm the devices and cause failure due to overheating (Anderson, Tannehill and Pletcher, 2016). For the cooling purpose, natural convection and conduction are commonly used on a low-power electronic system. Sometimes the cooling requirement is greater than the maximum cooling capacity of natural convection. Hence, the cooling method needs to be enhanced by integrating other methods with the existing ones, as long as the performance is improved while the power consumption remains unchanged.

A recent study about liquid cooling was done by Wu *et al.*, (2019) on numerical simulation of an immersed jet array impingement cooling device (IJAICD) with scattered returns. A multi micro-nozzles indirect liquid cooling was a novel structure for a cooling power module innovated by Pourfattah and Sabzpooshani, (2020) to enhance the performance of the jet impingement method. Ariyo and Bello-Ochende (2020) then introduced a construct design of subcooled microchannel heat exchanger which consumed deionized water as the cooling fluid while Cao *et al.* (2020) used a phase change material to design a liquid cooling strategy to achieve high-temperature uniformity of Li-ion battery under high-rate discharge. Liquid cooling transfers heat better than air cooling but also has drawbacks due to leaking and might damage the electronic components (Sohel Murshed and Nieto de Castro, 2017a).

In the research of micro-electromechanical systems (MEMS), air becomes the main medium chosen in the heat transfer proses due to its high reliability and being environmentally favored compared to liquid. In addition, air is the most abundant and natural cooling medium regardless of its lower heat transfer coefficient (lower specific heat). Because of these factors, air has a limited capability of dealing with a very large heat flux from high power electronics compared to liquid cooling. The air cooling system needs to combine both active and passive cooling to encounter these drawbacks, such as in a microchannel heat sink equipped with fan to boost the air flowing through the heat sink (Tijani and Jaffri, 2018). A numerical study on the triangular shape of the micro pin-fin has been investigated by Alam *et al.*, (2020). A study of various active cooling to assist the heat sink involving piezoelectric fans with multiple magnetic fans was introduced by Ma, Tan, and Li, (2014) and a study of an air-cooled heat sink was carried out by Youmin *et al.* (2014). The piezoelectric actuator was also used in developing high velocity of air using dual piezoelectric cooling jets (DCJ), innovated by Jang and Lee, (2014), while a hybrid synthetic jet was introduced by Trávníček and Vít (2015) in which two additional variants of reversible pulsating jets were investigated, namely synthetic (zero-net-mass-flux) jets and mixed pulsed jets (pulsed jets containing an additional blowing component).

The focus of this study is on the implementation of piezoelectric material in a cooling system by generating air flow to remove the hot air from the hotspot area. The mechanism of piezoelectric fan has garnered a lot of attention to further analyze the potential of piezoelectric fan in a cooling system. By principle, the piezoelectric fan needs to produce a high flow rate to disrupt the air boundary layer on a hot surface and replace it with new and cooler air, thus reducing the temperature of the hot surface. Multiple piezoelectric-magnetic fans (MPMF) innovated by Ma, Su, and Luo, (2013) and the latest publication of MPMF in radial orientation by Ma, Liao, and Hsieh, (2017) has improved the area of cooling while maintaining the power consumption of a single piezoelectric fan. Therefore, the advantages of MPMF will be the main focus of this study, especially on the design optimization and thermal analysis to validate the proposed design parameters of MPMF.

As for the current progress, the MPMF applies the influence of magnet in deflecting other passive fans in its mechanism with the same deflection equation as in the previous study. The effect of magnet is not shown theoretically in the equation, thus the performance of the MPMF cannot be validated theoretically. Since this equation involves both single piezoelectric fan (SPF) and MPMF (array-APMF and radial-RPMF), a mathematical model for each type of SPF and MPMF need to be considered. As for MPMF, the average deflection of the fans is influenced by the net applied force to the fans. There is still a lack of research on the comparison of the different orientations of MPMF so that the MPMF can perform at its most efficient level.

1.2 Problem Statement

The MPMF is proposed for a device that currently uses a microchannel heat sink with natural or forced convection. The MPMF is proposed to replace the conventional fan that is equipped together with the heat sink and to eliminate the drawbacks of the existing fan such as noise, extra power consumption, and extra weight.

The performance of MPMF is successfully proven experimentally and discovered to have high potential as an alternative cooling system for electronics. However, there is a lack of location of the magnet parameter in the equation of deflection of MPMF, even though it has a significant impact on the fan deflection. The MPMF also varies in array and radial orientation but there is no mathematical expression to represent the difference between both orientations. The optimization method of parameters in MPMF was previously identified using OFAT which is less accurate, time-consuming, and has no parameter interactions between the factors. In thermal analysis, the limitation of MPMF is not critically discussed which is very important to allocate the MPMF to the right device for optimal cooling efficiency.

To enhance the performance of MPMF, the mathematical model of MPMF needs to be established so that the performance of MPMF can be predicted by simulation and validated by experimental data. Therefore, there is a need to revise the characteristics and specifications of MPMF for better cooling performance and to find the optimal values of the contributing factors of the MPMF using the Respond Surface

Method (RSM) in the Design of Experiment (DoE) for better accuracy. The thermal performance of MPMF needs to be analyzed so that such a cooling system is placed at the right device and the cooling performance can be maximized. By replacing the conventional fan with MPMF, the purpose of cooling is maintained and the drawbacks are eliminated.

1.3 Research Objectives

The main objective of this study is to propose new criteria on an MPMF cooling system for electronic devices which enhances the velocity of air thus improve the thermal efficiency. The specific objectives of this study are:

1. To propose a mathematical modeling of multiple piezoelectric magnetic fans (MPMF) by varying the location of magnet, distance between magnet to length ratio, range of heat source power input and orientation of fans.
2. To improve the optimization method using the Design of Experiment (DoE) due to drawbacks of One Factor at a Time (OFAT) to optimize the location of magnet and distance between magnet to length ratio.
3. To analyze the thermal efficiency of MPMF at different orientations and capacities of heat source.
4. To validate the optimal results of the parameters using simulation analysis and experimental data.

1.4 Scope and Limitation of the Research

The proposed MPMF is mainly designed for a device that initially consumes natural convection with a microchannel heat sink. Sometimes, when the heat is hardly removed due to lower heat convection coefficient of air, a fan is needed to force the hot air leaving the device. The function of MPMF is to replace the conventional fan which consumes more power, more noise, and more weight compared to MPMF.

The driving fan of MPMF is a readymade piezoelectric fan bought from Piezo, (2016). The piezoelectric actuator is made from lead (plumbum) zirconate titanate (PZT). The performance of MPMF is restricted by the specifications of the driving fan to transfer the net force to the adjacent magnetic fans. This also affected the total net force transmitted to the adjacent passive fans. The dimension of the magnetic fans followed the dimension of the driving fan to consider there is no change has been made in terms of dimension of the fan. The piezoelectric fan used 240 alternating current voltage (VAC). Therefore, the fan needs an AC based electrical device throughout the study. However, the application of the MPMF is not restricted to AC only and the type of supply voltage could be modified according to the need of the device but is not the focus of the study.

The readymade piezoelectric fan is controlled by a function generator so that the frequency of the fan can be regulated. The range of safe temperature limit for an electronic component is 50-60ºC (Hetsroni *et al.*, 2002) and 60-100ºC for computer chips (Jajja, Ali and Ali, 2014; Sohel Murshed and Nieto de Castro, 2017b). Therefore, the MPMF is designed to reduce the temperature in the range of 60-100ºC.

The proposed MPMF is prepared for a device that emits a thermal output of less than 50W. This is justified by the benchmark paper Ma *et al.*, (2017) that applied a heat source of 35W. Therefore, the maximum heat source being applied in this study is put below 50W to compare the performance of MPMF with the benchmark.

1.5 Research Contributions

The focus of the study is mainly on the establishment of a fundamental analysis on MPMF. The contribution to knowledge about MPMF helps the researchers to continue the investigation of the potential of MPMF in the electronic cooling system.

Firstly, the contribution of the study is on the derivation of the equation regarding the deflection of single piezoelectric fan (SPF) attached with magnet. Previously the idea was tested experimentally in a laboratory and the consequences were seen in the temperature drop of the heat source. However, there was no equation of deflection that represented the significance of magnet to the deflection of the piezoelectric fan. Therefore, in this study, the equation of deflection of a single piezoelectric fan is derived as a function of magnet location and resonant frequency so that it can be used to predict the actual fan deflection precisely.

Secondly, the equation of deflection of each fan blade in MPMF was derived by considering two orientations; array (APMF) and radial (RPMF). The equation of deflection is influenced by the total force applied on each fan including the total repulsive magnetic force at different orientation of MPMF. The accuracy of the proposed equations is validated with the actual results from the experiments.

Thirdly, the Design of Experiment (DoE) with Response Surface Method (RSM) as one of the optimization method is applied to find the best value for the location of magnet and distance between magnet to length ratio. In the research of piezoelectric fans, most of the published papers used One Factor at A Time (OFAT) method which is found to have less accuracy, more time-consuming in completing the experiments and no parameter interactions can be established compared to DoE. Therefore, having more accurate values of the parameters results in better thermal results and analysis.

The final contribution is the extension of the thermal analysis of MPMF. The optimal size of heat source and orientation of MPMF have been determined using RSM. By providing these optimized results, more details are provided on the specifications and characteristics of MPMF as a potential cooling system for electronic devices.

1.6 Thesis Outline

Chapter 1 outlines the purpose of the study which is to optimize the parameters of MPMF in terms of the location of magnet and the distance between magnet to length ratio. The MPMF is tested with a thermal analysis on MPMF for various orientations and sizes of the heat source. The problem statement and scope of the study are clarified.

Chapter 2 is the background study of the development of piezoelectric fan in electronics cooling system. The MPMF has high potential as future cooler for electronics to substitute the conventional cooling fan. The forced convection principle applied on a heat sink is stimulated by the MPMF. The gap of the study is to improve the performance of MPMF by investigating the various location of magnet, the distance between magnets to length ratio and the orientation of the MPMF to gauge the average deflection of MPMF. The optimum deflection and resonant frequency results in maximum velocity which generates the maximum Reynolds number. The type of heat sink is also investigated so that the MPMF can be paired with the best type of heat sink. Thermal analysis is reviewed to find the limitations of the MPMF in cooling electronic devices and the performance of other piezoelectric fans compared with the proposed MPMF.

Chapter 3 focuses on the development of a mathematical modeling of MPMF by varying the location of magnet and distance between magnets to length ratio. The new derivation of equations is validated by experimental data. The experimental hardware, instrumentation, data acquisition system and software used for the experimental setup are elaborated. The experiments were initially conducted using one factor at a time (OFAT) to find the range of each parameter under investigation before running another experiment according to the DoE matrix table for the optimization process. Altogether, 4 parameters were selected to be optimized and a total of 6 experiments were conducted.

Chapter 4 presents the results for the four parameters under optimization; location of magnet, distance between magnets, fans orientation, heat source orientation, and size of the heat source. The relationship among all the parameters were discussed and the effect to the thermal analysis was overviewed. The performance of MPMF was compared with a previous study as well as the theoretical simulation. The efficiency of the proposed MPMF was highlighted as the key point of the proposed design compared to others.

Chapter 5 concludes the achievement of objectives of the study and recommends potential ideas for the MPMF casing and numerical analysis that could be implemented afterwards. A few recommendations are suggested so that the topic can be further investigated in the future.

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