DEVELOPMENT OF POWER GENERATION SYSTEM USING PIEZOELETRIC AND ELECTROMAGNETIC INDUCTION TECHNIQUES ON LAB-ON-A-DISC (LOD) FOR LOCALIZED HEATING

KARUNAN JOSEPH

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2017

University of Malaya

DEVELOPMENT OF POWER GENERATION SYSTEM USING PIEZOELETRIC AND ELECTROMAGNETIC INDUCTION TECHNIQUES ON LAB-ON-A-DISC (LOD) FOR LOCALIZED HEATING

KARUNAN JOSEPH

DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2017

University of Malaya

UNIVERSITY OF MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Karunan Joseph

Registration/Matric No: KGA120119

Name of Degree: Masters of Engineering Science

Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"):

DEVELOPMENT OF POWER GENERATION SYSTEM USING PIEZOELETRIC AND ELECTROMAGNETIC INDUCTION TECHNIQUES ON LAB-ON-A-DISC (LOD) FOR LOCALIZED HEATING

Field of Study:

BioMEMS

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date:

Subscribed and solemnly declared before,

Witness's Signature Date:

Name:

Designation:

University of Malaya

ABSTRACT

This thesis presents the development of a power generator on the Lab-on-a-Disc (LOD) for biomedical applications using two energy harvesting techniques. The first power generator was developed using piezoelectric films and the second power generator was developed using electromagnetic induction technique. The rotational environment during the operation of the disc was used by the power generators to harvest electrical energy using piezoelectric films and electromagnetic induction technique. For the first power generator, 6 pieces of piezoelectric film (thin film PVDF) are embedded on the disc with a small circular magnet at the end of each film to resemble a cantilever system. A permanent magnet was installed on the stationary base, close to the outer edge of the disc. As the power generator disc rotates, the small magnet attached at the outer end of the piezoelectric film will be attracted to the permanent magnet and bends the film. This mechanism induces mechanical vibration to the piezoelectric film and generates electrical power. The second power generator disc is embedded with 6 stacks of copper coils placed over a set of N52 neodymium permanent magnets. The permanent magnets provide strong magnetic field over the power generator disc and as the disc rotates, the copper coils cuts the magnetic field and current will be induced in the copper coil stacks. The piezoelectric film based generator was able to produce 24 microWatt at 83.775 rad/s (800RPM) while the electromagnetic induction based power generator produced 125 miliWatt at 157.08 rad/s (1500RPM). Based on the power generation characteristic of each technique, the best power generator was used to demonstrate a localized heating system on the disc. Localized heating technique can be used to perform on-disc incubations and thermal cycling for numerous biomedical applications. Due to ability to produce higher electrical power, the localized heating system was embedded with the electromagnetic induction

University of Malaya

based power generator. The system reported to achieve up to 58.62°Celsius at spinning speed of 230.38 rad/s (2200RPM).

University of Malaya

ABSTRAK

Tesis ini membentangkan pembangunan penjana kuasa pada “Lab-on-a-Disc (LOD)” untuk aplikasi bioperubatan menggunakan dua teknik penuaian tenaga elektrik. Penjana kuasa pertama telah dibangunkan menggunakan filem piezoelektrik dan penjana kuasa yang kedua telah dibangunkan menggunakan teknik induksi elektromagnetik. Keadaan LOD yang berputar semasa operasi digunakan untuk menuai tenaga elektrik menggunakan filem piezoelektrik dan teknik induksi elektromagnetik. Untuk penjana kuasa pertama, 6 keping filem piezoelektrik (PVDF filem nipis) dipasang pada LOD dengan magnet bulat kecil pada hujung setiap filem untuk memimik sistem cantilever. Magnet kekal dipasang pada badan asas LOD yang tidak bergerak sama dengan LOD, tetapi berhampiran dengan hujung LOD tersebut. Apabila LOD penjana kuasa berputar, magnet kecil yang dilampirkan di hujung luar filem piezoelektrik akan tertarik kepada magnet kekal dan membengkokkan filem peizoelektrik. Mekanisme ini menghasilkan getaran mekanikal pada filem piezoelektrik dan menghasilkan kuasa elektrik. LOD penjana kuasa kedua mempunyai 6 gegelung tembaga yang ditempatkan di atas satu set magnet kekal neodymium N52. Set magnet kekal tersebut menyediakan medan magnet yang kuat ke atas LOD penjana kuasa dan semasa LOD tesebut berputar, gegelung tembaga akan memotong medan magnet dan arus akan dihasilkan dalam setiap gegelung tembaga tersebut. Penjana berasaskan filem piezoelektrik berjaya menghasilkan 24 mikroWatt pada 83.775 rad/saat (800RPM) manakala penjana kuasa berasaskan induksi electromagnet berjaya menghasilkan 125 miliWatt pada 157.08 rad/saat (1500RPM). Berdasarkan ciri penjanaan kuasa kedua-dua teknik, penjana kuasa yang terbaik akan digunakan bagi sistem pemanasan setempat pada LOD. Teknik pemanasan setempat boleh digunakan untuk melaksanakan proses inkubasi dalam LOD dan proses kitar pemanasan untuk pelbagai aplikasi bioperubatan. Oleh kerana penjana kuasa berasaskan induksi elektromagnetik berjaya menghasilkan kuasa elektrik yang lebih tinggi, sistem

University of Malaya

pemanasan setempat telah diintegrasikan dengan penjana kuasa berasaskan induksi elektromagnetik. Sistem ini dilaporkan mencapai 58.62 ° Celsius pada 230.38 rad/saat (2200RPM).

University of Malaya

ACKNOWLEDGEMENTS

First of all, I would like to convey my sincere gratitude to Professor Ir. Dr. Fatimah Ibrahim and Professor Dr. Jong Man Cho for their tireless guidance, patience, supervision and motivation throughout this research. I could not have asked for better mentors for my study. They have shared their valuable time, insights and values to me for the completion of this study. Special thanks to Professor Dr. Marc Madou from University of California Irvine for his advice and constructive criticism.

Appreciation goes to Fundamental Research Grant Scheme (FRGS:FP042-2013B) and University of Malaya Research Grant (UMRG: RG009A-13AET) for their support for this research. Appreciation also goes to Yayasan Sultan Iskandar Johor for their Special Equipment Grant which helped to complete this research successfully. I would also like to thank Faculty of Engineering for providing facilities and the exposure required for undertaking this research.

Warm thanks to all my colleagues in the Centre for Innovations in Medical Engineering (CIME), in particular Aung Thiha, Abkar Ahmed Sayad, Shah Mukim Uddin, Dr Wisam, Dr Gilbert, Dr Mehdi, and Dr Bashar for their brilliant ideas, stimulating discussions and selfless support throughout the research.

Last but not least, special thanks to my mother, sister, and brother who are a part of whom I am today and the better me tomorrow.

University of Malaya

TABLE OF CONTENTS

University of Malaya

University of Malaya

LIST OF FIGURES

University of Malaya

LIST OF TABLES

University of Malaya

LIST OF SYMBOLS AND ABBREVIATIONS

LOD	:	Lab on a Disk
CD	:	Compact Disc
PVDF	:	Polyvinylidene Fluoride
DEP	:	Dielectrophoresis
PCR	:	Polymerase Chain Reaction
AC	:	Alternating Current
POC	:	Point of Care
RPM	:	Revolution per minute
TPMS	:	Tire Pressure Measuring System
PMMA	:	Polymethyl Methacrylate
PSA	:	Pressure Sensitive Adhesive
CNC	:	Computer Numerical Control
CAD	:	Computer Aided Drawing
V_{pp}	:	Voltage Peak-to-Peak
DC	:	Direct Current
TWI	:	Two Wire Interface
PID	:	Proportional-Integral-Differential
SWG	:	Standard Wire Gauge
AWG	:	American Wire Gauge
Rad/s	:	Radians Per Second
TTL	:	Transistor-Transistor Logic

University of Malaya

LIST OF APPENDICES

University of Malaya

CHAPTER 1: INTRODUCTION

1.1 Overview

Point-of-care (POC) diagnostic systems and technologies have grown significantly in the recent years. The growth is in line with the high demand for diagnostic devices which are portable, cost-effective, fast, and power-effective. Lab-on-a-Disc (LOD) is one of the technology that can emerge as the best POC solution with its potential of miniaturization, portability, and automation (Aeinehvand *et al.*, 2015). LOD, or also known as centrifugal microfluidic disc manipulates the motion of fluid confined inside the disc through the geometry of channels, chambers and valving concepts (Al-Faqheri *et al.*, 2013; Kazemzadeh *et al.*, 2013). It functions by the centrifugal force which are obtained from the rotation of the disc. The variation of rotational speed (denoted in radians per second (rad/s) and measured in revolutions-per-minute (RPM)) changes the centrifugal force applied to the fluids confined inside the disc (Smith *et al.*, 2016; Thio, Soroori, *et al.*, 2013). The change in centrifugal force is used to sequence the propulsion of the fluid from the center to the outer edge of the disc. This method of fluidic control and propulsion can be achieved by using a simple controllable spin base system. Electricity, in this case, is only needed to power the spin-base system which consists of a motor, control system and computing unit (PC). That is the fundamental operation of the LOD system. This is one of the biggest advantage in extending LOD into POC diagnostic device.

In general, LOD offers a solution for biochemical assay automation in terms of fluid sequencing, mixing, metering and storage in micro domain. However, power-effectiveness is still a questionable factor for LOD when performing complex bio-assays involving incubation, heating and electrochemical detections (Höfflin *et al.*, 2015; Smith *et al.*, 2016). This is because the electrical power supplied to the spin-base system cannot be directly supplied to the spinning disc while is in rotational mode.

University of Malaya

Currently, most of experiments involving incubation, heating or electrochemical detection are conducted using external peripherals which are driven by additional power supply (K. Abi-Samra, Clime, *et al.*, 2011; K. Abi-Samra, Hanson, *et al.*, 2011; Kameel Abi-Samra *et al.*, 2013; Martinez-Duarte *et al.*, 2010). Inclusion of this external peripherals reduces the portability and power-effectiveness, and increases the complexity of LOD system. In 2015, a group researchers from Germany developed a wireless power transfer system to address this problem (Höfflin *et al.*, 2015). The approach is able to power some of the power-consuming application, however it requires the primary coil to be powered externally in order to work. This further increases the complexity of the system and still requires the primary coil to be powered externally. Therefore, the development of an integrated power generating system on LOD is important to restore the portability and power-effectiveness while capable of performing power-hungry applications.

The aim of this thesis is meet the limitation of current LOD and introduce a power generator on LOD, which harness the power from rotational environment of LOD and channels the power for localized heating on LOD. This is to solve the current limitation of LOD by performing the most energy consuming active application on LOD, using energy harvested from the rotational environment of LOD itself.

University of Malaya

1.2 Research Objective

The objective of this research is to develop an energy harvesting-based power generator system for power consuming application on LOD using piezoelectricity and electromagnetic induction methods. The detailed sub-objectives are as follows:

1) To develop a piezoelectric film power generator disc.
2) To develop an electromagnetic power generator disc.
3) To develop a localized heating system on LOD using the best power generator between piezoelectric and electromagnetic technique.

1.3 Scope of Work

This research focuses on the development of a power generator system for the use of assays that consumes electrical power on LOD using energy harvesting techniques. The energy harvesting techniques studied in this research are piezoelectricity and electromagnetic induction. Piezoelectricity is achieved by inducing mechanical vibration from the spinning environment of LOD to the piezoelectric film embedded on a customized LOD. The power generation while the disc is spinning at different spinning speed was recorded using a customized spin chunk to provide electrical connection from the disc to an oscilloscope. Meanwhile electromagnetic induction is achieved by inducing stacks of copper coils embedded in another customized LOD over the permanent magnets installed at the bottom of the LOD. A customized wireless voltage measuring device was developed to fit on the LOD to record the power generation data. A localized heating system was developed using the power generator disc with the highest power generation capacity. The localized heating system is an essential enhancement for LOD system to perform incubation, wax-valving and pneumatic pumping in complex bioassay application. The developed integrated localized heating system was tested with a wireless embedded temperature monitoring system to observe and evaluate the heating capacity of the system.

1.4 Thesis Organization

This thesis is organized as follows:

Chapter 1 provides the background information pertaining to the work established in this thesis. It highlights the general problem statement, current works, specific objectives and scope of work of this thesis.

Chapter 2 describes the literature review and background study of the whole project. It covers the review on methods of fluidic propulsion in microfluidic and introduction of LOD. Besides that, it also covers the background study on the energy harvesting technologies and energy harvesting on rotating environments.

Chapter 3 presents the research methodology and protocols that are followed to achieve the objective. It explains the LOD fabrication techniques, the methods of developing both piezoelectric film and electromagnetic induction based power generator LODs. Moreover, the chapter also outlines the protocol of experiment for both power generating methods.

Chapter 4 focuses on the results and the discussions of the experiments conducted. The piezoelectric film based power generator was discussed followed by the electromagnetic induction based power generators.

Finally, Chapter 5 presents the overall conclusion based on the project that has been conducted.

University of Malaya

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter covers the literature work on the fundamental information regarding Lab-on-a-Disc (LOD), active applications on LOD, and energy harvesting technologies, and a concise summary on energy harvesting techniques on rotating platform.

2.2 Lab on a Disc Technology

2.2.1 Fluidic Propulsion Technique

In microfluidic platforms, there are various methods to propel fluids or suspended particles from one chamber to another for mixing or reaction. One of the main consideration in the microfluidic platform is the pressure needed for this fluid propulsion to happen inside capillaries as the channel's hydraulic diameter reduces (M. Madou *et al.*, 2006).

Table 2.1 Microfluidic propulsion techniques comparison. Adapted from (M. Madou *et al.*, 2006).

FLUID PROPULSION MECHANISM				
COMPARISON	**CENTRIFUGE**	**PRESSURE**	**ACOUSTIC**	**ELECTROKINETIC**
VALVING SOLVED?	Yes for liquid, no for vapour	Yes for liquid, no for vapour	No solution shown yet for liquid or vapour	Yes for liquid, no for vapour
MATURITY	Products available	Products available	Research	Products available
PROPULSION FORCE INFLUENCED BY	Density and viscosity	Generic	Generic	pH, Ionic strength
POWER SOURCE	Rotary motor	Pump, Mechanical roller	5 to 40 V	10 kV
MATERIALS	Plastics	Plastics	Piezoelectric	Glass, Plastics
SCALING	L^3	L^3	L^2	L^2
FLOW RATE	From less than 1 $nl.s^{-1}$ to greater than 100 $\mu l.s^{-1}$	Very wide range (less than $nl.s^{-1}$ to liter s^{-1})	20 $\mu l.\ s^{-1}$	0.001-1$\mu l.\ s^{-1}$)
GENERAL REMARKS	Inexpensive CD drive, mixing is easy, most samples possible (including cells). Better for diagnostics	Standard techniques. Difficult to miniaturize and multiplex	Least mature of the four techniques. Might be too expensive. Better for smallest samples.	Mixing difficult. High voltage source is dangerous and many parameters influence propulsion, better for smallest samples

University of Malaya

Table 2.1 compares the four popular fluid propulsion means (M. J. Madou, 2002). Mechanical pumps have to produce higher pressure as the channel gets narrower. However, the centripetal force and pressure are dependent on volume (L^3) of the fluid the chamber/reservoir holds. Piezoelectric and electro-osmotic pumping forces are surface-dependent (L^2). In micro-domain, these type of forces are much more favorable because the propulsion forces required are lower. But the implementation are often complex and troublesome.

Another type of fluid propulsion method is acoustic streaming mechanism. It is based on the induction of sound field oscillation. This method is able to introduce mixing as well as non-reactive with the chemical properties of the fluids but it requires special equipment and complex to be implemented (Miyazaki *et al.*, 1991). Electro-osmosis pumping is another different method of fluid propulsion that is easily implementable and requires no moving parts. The drawbacks are that it needs very high voltage (1-30) kV power supply and has direct contact with the fluids (Harrison *et al.*, 1994; Jorgenson *et al.*, 1983). These lead to the idea of centrifugal pumping method. Centrifugal pumping mechanism are able to provide flow rate of less than $10nls^{-1}$ to higher than $100\mu ls^{-1}$. Disc geometries, rotational speed, and fluid properties are essential to determine the flowrates. The advantages are that it is non-reactive to the physiochemical properties of the fluid and even electrical properties (M. Madou *et al.*, 2006). Besides that, this method and mechanism can be easily miniaturized and able to perform multiplexing (Ibrahim *et al.*, 2010; M. Madou *et al.*, 2006; M. J. Madou, 2002). Integration of this pumping mechanism with microfluidic platform is known as centrifugal microfluidic platform. These further leads to the introduction of “Lab-on-a-CD or Lab-on-a-Disc (LOD)”, where complex biochemical assay processes are translated into fluidic networks on centrifugal microfluidic platform. LOD is also regarded as Lab-on-a-CD because the dimensions and look are similar to compact discs (CDs). Technically, a centrifugal microfluidic disc has fluidic networks within the disc rather than acting as an optical digital data storage CD (Gorkin *et al.*, 2010). It functions by spinning the disc to generate centrifugal forces on the fluids confined inside the chambers on the disc. The manipulation of the spinning speed allows the sequencing of the fluid propulsion in the disc (K. Abi-Samra, Clime, *et al.*, 2011; K. Abi-Samra, Hanson, *et al.*, 2011). On top that, this centrifugal microfluidic disc also functions according to the manipulation and design of the channel's geometry, size of the chambers and a number of passive and active valving concepts (Al-Faqheri *et al.*, 2013; Thio, Ibrahim, *et al.*, 2013).

Figure 2.1: An example of Lab-on-a-disk system.
Adapted from (Czilwik *et al.*, 2015)

2.2.2 LOD Theory of Operation

The operation of lab-on-a-disc is driven by centrifugal, Coriolis and Eular forces present when the disc is spun on a rotating platform. These three forces are manipulated to effectively propel and control the fluidic sequencing within the disc. An example of conceptual drawing are shown in Figure 2.2. The figure depicts forces acting on a reservoir (blue square) which are located at a radial distance of $\bar{r}$ from the center of the disc at O. F_ω is the force contributed by centrifugal force at an angular speed and direction of ω. F_C and F_E are the Coriolis and Euler forces acting on the liquid in the reservoir, respectively.

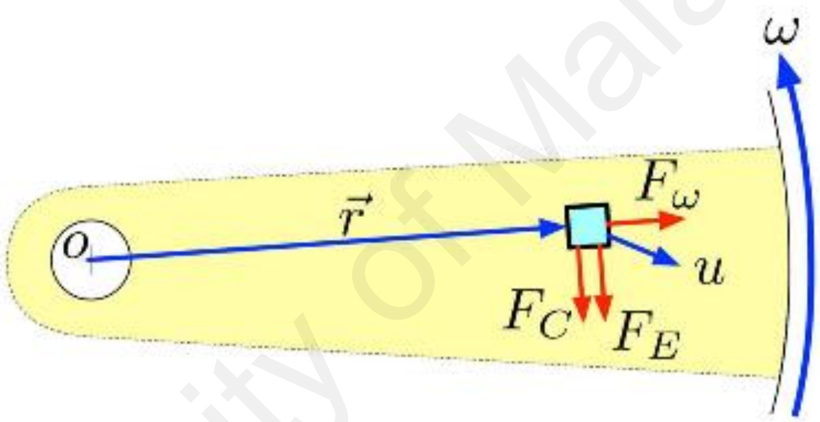

Figure 2.2: Conceptual drawing on forces acting on LOD
Adapted from Smith *et al.* (2016).

University of Malaya

The centrifugal force ($P_{centrifugal}$) is the main driving force used to propel the fluid from the center of the disc to the outer rim of the disc. It acts radially outward and proportional to the square of the angular velocity. The force required to push the fluid, from one inner radial point to another outer radial point can be calculated using the following equation [1]:

$$P_{centrifugal} = \rho\omega^2 \Delta r \bar{r} \tag{1}$$

where ρ is the density of the liquid used, ω is the disc angular velocity in radians per second (rad/s), Δr is the difference of top and bottom liquid levels at rest relative to the disc's center and $\bar{r}$ is the average distance of the liquid from the center of the disc. All these parameters are required to calculate the rotational speed needed to achieve the centrifugal force in order to sequence the fluid flow in the disc. Another important force which determines the flowrate of fluid inside the microchannel in the disc is capillary force (P_{cap}). This force mainly driven by the hydraulic diameter of the channels and hydrophobicity of the channel's surface. This force is calculated by the following equation [2]:

$$P_{cap} = \frac{4\cos\theta_c \gamma_{la}}{D_h} \tag{2}$$

where θ_c is the contact angle of the liquid with the channel's surface, γ_{la} is the liquid-air surface energy, and D_h is the channel's hydraulic diameter. In most applications, the fluidic sequencing is controlled using the combination of $P_{centrifugal}$ and P_{cap}. This is because the flow of liquid confined inside the reservoirs in the disc will be inhibited by P_{cap} and will only start when $P_{centrifugal}$ is dominant.

2.2.3 Energy Demanding Operations on LOD

Generally, centrifugal microfluidic disc is passive and operates only by the applied centrifugal force contributed from spinning of the disc. This limits the capability of the disc to be able to only perform basic fluidic techniques such as mixing, valving, metering, separation and siphoning (Gorkin *et al.*, 2010; M. Madou *et al.*, 2006). In order to integrate more complex biomedical assays and biochemical techniques, active mode was introduced (Cho *et al.*, 2007; Gorkin *et al.*, 2010). Centrifugal microfluidic discs which are enhanced with additional peripherals to perform detections, analysis, and monitoring single-handedly and known as active mode operation. A few examples of the additional peripherals made are the generation of thermal energy from halogen lamps/lasers, thermoelectricity in performing Polymerase-Chain-Reaction (PCR) amplification, wax-valves triggering options, fluidic transfer motions and pneumatic pumping applications for efficient fluid handling. Besides the thermal energy generation, electrical interface was applied to the disc for the applications of electrochemical glucose concentration measurements, sample enrichments using dielectrophoresis (DEP) and also electrochemical velocimetry on LOD to measure the fluid flow while the disc is rotating (K. Abi-Samra, Hanson, *et al.*, 2011; Al-Faqheri *et al.*, 2013; Amasia *et al.*, 2012; Focke *et al.*, 2010). These techniques are great breakthroughs in the field LOD. However, inclusion of these additional peripherals limits the portability and increases complexity of the system as a point-of-care (POC) diagnostic device. The limitations caused by the additional peripherals are listed in Table 2.2.

Table 2.2: Summary of energy-drawing applications on centrifugal microfluidic discs

Energy Drawing Application on CD	Method	Estimated Power Consumption	Limitation
Handling And Storage of Liquid Using Waxes(K. Abi-Samra, Hanson, *et al.*, 2011)	Infrared (IR) Radiation	75 Watt	High power usage. Bulky additional setup
Thermal-Pneumatic Liquid Pumping(K. Abi-Samra, Clime, *et al.*, 2011)	Infrared (IR) Radiation	75 Watt	High power usage. Bulky additional setup
Vacuum And Compression Valving Concept (Al-Faqheri *et al.*, 2013)	Forced Convection Heat Transfer	2000 Watt	High power usage. Heating of non-desired location
Thermo-Pneumatic Push And Pull Liquid Pumping (Thio, Ibrahim, *et al.*, 2013)	Forced Convection Heat Transfer	2000 Watt	High power usage. Heating of non-desired location
Rapid Amplification PCR With Integrated Heating And Cooling(Amasia *et al.*, 2012)	Thermoelectricity	1000 Watt	Disc has to stopped to apply the heat in the middle of operation
Integration Of Carbon-Electrode Dielectrophoresis (Martinez-Duarte *et al.*, 2010)	Dielectrophoresis	50 Watt	External connection using slip ring arrangement
Whole Blood Analysis Utilizing Electrochemical (Li *et al.*, 2013)	Electrochemical	50-200 Watt	Additional slip ring arrangement required

University of Malaya

Velocimetry In Monitoring Flow Real-Time (Kameel Abi-Samra *et al.*, 2013)	Electrochemical	50-200 Watt	Additional slip ring arrangement required

2.2.3.1 Thermal Energy Drawing LOD Applications

Most of the applications that require additional peripheral for LOD operations are thermal energy demanding operations. In addition, it is also the most energy consuming application among others. The main usage of thermal energy in LOD is for valve actuation, pneumatic pumping and incubations. This is why the application of the power generator is focused on localized heating techniques. The localized heating techniques are capable of solving more than half of the current limitation of LOD while restoring power efficiency and promoting more enhancement on LOD. As a reference for this application, a summary of existing applications that require thermal energy and the temperature range is listed in Table 2.3.

Table 2.3: Temperature requirements of current thermal energy-drawing applications on the CD.
Adapted from (Joseph *et al.*, 2015)

Thermal Energy Drawing Applications	Temperature	
	Minimum	**Maximum**
Liquid Handling And Storage Using Waxes(K. Abi-Samra, Hanson, *et al.*, 2011)	51.6 ˚C	62.7 ˚C
Thermal-Pneumatic Liquid Pumping(K. Abi-Samra, Clime, *et al.*, 2011)	25 ˚C	57 ˚C
Vacuum And Compression Valving Using Paraffin-Wax(Al-Faqheri *et al.*, 2013)	26 ˚C	57.2 ˚C
Thermo-Pneumatic Push And Pull Liquid Pumping(Thio, Ibrahim, *et al.*, 2013)	27 ˚C	50˚C
Rapid Amplification PCR With Integrated Heating And Cooling (Amasia *et al.*, 2012)	60˚C	95˚C

2.2.4 LOD Spin Stand Evolution

In order to function, LOD requires a platform where the disc will be mounted and spun according to the spinning protocols. The platform is known as LOD spin stand. The basic

University of Malaya

setup of a spin stand requires a controllable motor, control system (PC), control software for speed and other controls and imaging setup (CCD camera for analysis during the disc is being spun) (Henderson *et al.*, 2016; Ibrahim *et al.*, 2010; Kazemzadeh *et al.*, 2013). Figure 2.3(1) shows the basic setup of spin stand in University of California, Irvine, USA.

To suit the applications of thermal based active mode, this spin stand was modified to add halogen lamps and laser heaters (K. Abi-Samra, Clime, *et al.*, 2011; Al-Faqheri *et al.*, 2013). Several other researchers also mounted heat guns and thermoelectric heaters for similar applications (Amasia *et al.*, 2012; Thio, Ibrahim, *et al.*, 2013). Another researcher modified the spin stand with a slip ring to the rotor to perform dielectrophoresis (DEP) on LOD (Martinez-Duarte *et al.*, 2010). This particular setup is shown in Figure 2.3(2). This was one of the first method to allow direct electrical interface with the disc, while the disc is spinning. Application of DEP on LOD opens a whole new branch of research in terms of detection techniques on LOD since only optical based detection techniques were used before. However, there were several issues pertaining this method. It is highly expensive to custom-make the rotor and slip ring and the friction causes the slip ring to wear of often (Smith *et al.*, 2016). Besides that, the slip ring method also limits the type of connection and communication method to be used to the disc.

Focusing on this matter, another group of researchers from Germany came up with an inductive coupling method to supply power to the disc. This method allows active electronics embedded on the disc for actuations, detections, communication and monitoring while the disc is spinning without direct electrical connection. The electrical power were transferred wirelessly from the primary coil embedded on the spin stand to the secondary coil embedded on the disc (Delgado *et al.*, 2016; Höfflin *et al.*, 2015). The conceptual setup of the system is shown in Figure 2.3(3). The concept solves most of the issues with conventional method of establishing electrical interface with the disc while

University of Malaya

spinning and potential to be expended for new methods of valve actuations on LOD. The drawbacks are however, it requires additional power supply for the primary coil and it will add extra load to the motor as the disc will be heavier with secondary coils and other electronics (Smith *et al.*, 2016).

These drawbacks lead to the introduction of sustainable power generators to be embedded on LOD. The approach taken for that is by employing energy harvesting technology on to LOD system and apply it to meet the need for energy-hungry application on the disc.

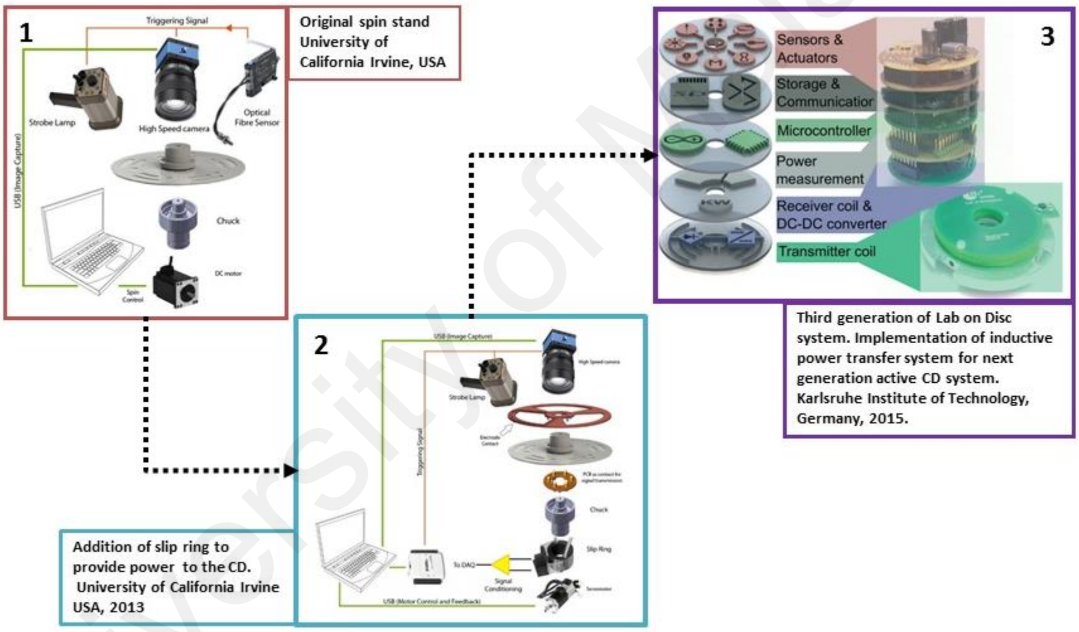

Figure 2.3: The evolution of Lab-on-a-disk spin stands.

The evolution of spin stands for LOD since the beginning form passive application (1), to active DEP application on LOD (2), and the wireless power on LOD for all active application (3). Modified from original in (Smith *et al.*, 2016).

2.3 Energy Harvesting Technology

Process of transforming ambient energy into a useful electrical energy are called as energy harvesting or energy scavenging. Examples of ambient energy are kinetic energy from vibrating system, thermal energy from warm environment, and solar energy from

University of Malaya

sunlight. In general, energy harvesting takes place without or minimally affecting the host system's nature of work (S. Roundy *et al.*, 2003; S. J. Roundy, 2003). Recent innovations in low-power electronics further facilitate the application of energy harvesting to power these electronics (Amirtharajah *et al.*, 1998). The applications that are widely using energy harvesting system are unmanned vehicles, medical sensors, health monitoring systems and rechargeable batteries (Priya *et al.*, 2009). There are several energy harvesting methods to convert the ambient energy into usable electrical energy. In terms of thermal energy conversion, thermoelectricity is used to convert heat into electrical energy. For solar radiation, photovoltaic materials are utilized. To convert mechanical energy into electrical energy, there are several conversion mechanisms which can be applied. For example, electromagnetism can be used by placing permanent magnets on the system which vibrates or moves to induce electric current in a coil of conductive wire. Piezoelectric materials which produce electrical potential when it deforms are also widely used to convert mechanical energy (Beeby *et al.*, 2006). Another method for mechanical energy conversion is electrostatic. The vibration of the host system changes the capacitance of the initially charged electrostatic harvesting system to produce current source (Torres *et al.*, 2006). However, the electrostatic based energy harvesting system would require additional power source to initially charge the system in order to work.

Looking back into the LOD system's environment, the most abundant ambient energy available for the disc is kinetic energy which is contributed by the spinning nature of the disc. In that case, this thesis will focus on kinetic energy based energy harvester to achieve the objective. That concludes the scope of energy harvesting conversion mechanism that will be utilized in this thesis which are electromagnetic and piezoelectric based energy harvesting system. Electrostatic system is not considered as it requires additional power to initially charge the system before it could work.

University of Malaya

2.3.1 Energy Harvesting in Rotational Environments

Structures that continuously move especially rotating structures are one of the main targeted environment for placement of energy harvesting system. This is because of the abundance of kinetic energy available to be converted to useable electrical energy (Joyce, 2011). Windmill turbines are one of the environment which are very optimum for energy harvesting. Taking advantage of this scenario, a group of research worked on powering a Simple Harmonic Motion (SHM) device by using different energy harvesting system, for example, piezoelectricity, thermoelectric, and photovoltaic (Carlson *et al.*, 2011). The piezoelectric energy harvester in a cantilever beam configuration was placed in the blade of the turbine. The photovoltaic energy harvester was mounted on the outside of the blade. The 140 cm^2 photovoltaic cell which has power density of 1.67 mW/cm^3 was able to generate up to 235 mW. Another energy harvester based on thermoelectric was integrated into the blade. This energy harvester was able to produce up to 0.1 mW from a temperature gradient of 10℃.

Another group of researchers targeted a ship's rotating propeller to harvest energy. They particularly focused on electromagnetic energy harvester with different methods of application. The system was able to generate 80 mW at 15.70 rad/s (150RPM). A similar approach was carried out on a rotating wheel using a pendulum-type electromagnetic harvesting system. The system was made of three permanent magnets and an adjustable linkage which allows control of the natural frequency setting.

In a Tire Pressure Measuring System (TPMS) study, a number of researcher studied placement of energy harvesting system inside the automobile (Manla *et al.*, 2009). They particularly examined a piezoelectric based generator to power the TPMS sensor. In the design, the piezoelectric device with a tube consisted of a ball bearing was placed at the end of the sensor. As the tire rotates, the ball bearing impacts the piezoelectric device.

The prototype managed to produce 12 µW at 20.94 rad/s (200RPM). Similarly, another researcher managed to produce up to 70 µW/cm^3 by using piezoelectric patches mounted on the tire walls (Youfan Hu *et al.*, 2012; Y. Hu *et al.*, 2011). The power was generated by deformation of the tire as it rotates.

Industrial environment is one of the places where rotational systems are abundant and energy harvesting system can be applied. For example, the placement of a rotational generator on a spinning machine to harvest energy from its rotational kinetic motion (Toh *et al.*, 2007; Toh, Mitcheson, Holmes, *et al.*, 2008; Toh, Mitcheson, & Yeatman, 2008). The generator consists of an imbalanced mass which was fixed to its rotor and then positioned on the rotating machine parallel to the host's axis of rotation. Electricity is generated when the imbalanced mass spins the generator's rotor caused by the gravitational force and centrifugal effects. This generator system was able to produce about 10 mW at rotational speed of 25.13 rad/s (240RPM). Focusing on a similar environment, a group of researchers worked on investigation of a piezoelectric energy harvesting system on rotating machineries. The energy harvester system was made of a cantilever beam with a mass on the tip. The system was fixed on the host with the beam pointing away from the center of rotation (Khameneifar *et al.*, 2011). The system was able to harvest up to 7.7 mW at a frequency of 22 Hz. Another similar system with limited self-tuning capability was examined because the variation in rotational speed alters the tension in the beam (Gu *et al.*, 2010). This contributes to altered natural frequency of the beam. In the experiment, the driving frequency was varied from 6.2 Hz to 16.2 Hz. With the self-tuning capability, the driving frequency and resonance frequency matches at 13.2 Hz, where the harvester was able to produce 0.7 mW.

University of Malaya

Table 2.4: Summary of rotational energy harvesting methods and achievable power output. Adapted from (Joseph *et al.*, 2015)

Method	Piezoelectric	Thermoelectric	Photovoltaic	Electromagnet
Wind Turbine Blades(Carlson *et al.*, 2011)	*3.125μW*	*0.1 mW*	*235 mW*	*N/A*
Rotating Propeller of a Ship(Conrad, 2007)	*N/A*	*N/A*	*N/A*	*80 mW*
Rotational Generator on Spinning Machine(Toh *et al.*, 2007; Toh, Mitcheson, Holmes, *et al.*, 2008; Toh, Mitcheson, & Yeatman, 2008)	*N/A*	*N/A*	*N/A*	*10 mW*
Energy Harvester on Rotating Wheel(Wang *et al.*, 2010)	*N/A*	*N/A*	*N/A*	*Few mW*
Energy Harvester in Automobile Tires - Pulley System(Manla *et al.*, 2009)	*12 μW*	*N/A*	*N/A*	*N/A*
Energy Harvester in Automobile Tires - Piezoelectric Patches(Y. Hu *et al.*, 2011)	*70 μW*	*N/A*	*N/A*	*N/A*
Piezoelectric Beams on Rotating Machinery(Khameneifar *et al.*, 2011)	*7.7 mW*	*N/A*	*N/A*	*N/A*
Piezoelectric Beams on Rotating Machinery *- limited self-tuning(Gu & Livermore, 2010)*	*0.7 mW*	*N/A*	*N/A*	*N/A*

2.3.2 Piezoelectric-based Energy Harvesting

Piezoelectricity materials become polarized electrically when mechanical strain is applied and the polarization is proportional to the strain applied. Certain piezoelectric materials are also mechanically strained when external electrical energy is applied to it. When voltage is applied across the material, the polarization will cause a mechanical stress/strain to the material (Goldfarb *et al.*, 1999; Khameneifar *et al.*, 2011; Sodano *et al.*, 2004).

In general, there are two types of high-energy density piezoelectric. Piezoelectric polymer, such as Polyvinylidene Fluoride (PVDF) has the highest piezoelectric voltage constant meanwhile relaxor-based single crystal, such as Lead Zirconate titante (PZT) have the highest piezoelectric voltage constant (Anton *et al.*, 2007; Erturk *et al.*, 2011;

University of Malaya

Priya & Inman, 2009). The challenge is in the synthesis of both type. The synthesis of both type is challenging and expensive. Thus, the current outlook for mass application is on improving the properties of polycrystalline ceramics. Current development in the production of high-energy density materials covers single crystals, ceramics, polymers and thin films.

In this thesis, PVDF polymer film were used for the piezoelectric power generator. It is a high-molecular weight polymer. PVDF is approximately half-crystalline and half amorphous which consist of chains that exhibit a short- and long-term ordering crystalline regions. It has been successfully utilized as Non-Destructive Evaluation (NDE) transducers in pulse-echo, through-transmission and acousto-ultrasonic techniques to monitor curing (Chen *et al.*, 1995; Harsányi, 2000; Hyunuk Kim *et al.*, 2009; Lee *et al.*, 1990; Smolorz *et al.*, 1996).

On top of that, PVDF material are mechanically sturdy and resilient to most chemicals. It also able to perform as a good piezoelectric even at microwave frequencies (Smolorz & Grill, 1996). Compared to other commonly used materials of piezoelectric, PVDF has very high Piezoelectric Voltage Constant (g_{33}). The comparison are shown in Table 2.5.

Goldfard *et al*. concluded that piezoelectric materials achieve higher efficiency at frequencies within the resonant frequency of the material (Beeby *et al.*, 2006; Goldfarb & Jones, 1999; HeungSoo Kim *et al.*, 2011; Sodano *et al.*, 2004). Equation (3) describes the electrical behavior of the piezoelectric material.

$$D = \varepsilon E + d\sigma \tag{3}$$

where vector D is the electric displacement, E is the electric field vector, ε is the dielectric constant, d is the piezoelectric strain coefficients and σ is the mechanical stress.

Table 2.5: Comparison between commonly used piezoelectric materials and PVDF

Material	Relative dielectric constant, $\varepsilon/\varepsilon_0$	Piezoelectric constant d_{33} (pC/N)	Piezoelectric voltage constant, g_{33} (10^{-3} V m/N)
$BaTiO_3$	1700	191	12.6
Quartz	4.5	2.3 (d 11)	50.0 (g 31)
PVDF	13	−33	−339.0
PZT-4	1300	289	25.1
$BaTiO_3$	1700	191	12.6

2.3.3 Electromagnetic-based Energy Harvesting

Since early 1930s, electromagnetism has been used to generate electricity to power the various. Most of the electromagnetic generators available today are based on rotation and used in a number of application with different range of power scale. It can be used to harvest micro- to milli-Watt range of power using rotational and linear devices. The efficiency of an electromagnetic generator however, depends on size and design.

Electromagnetic induction method is one of the most prominent and efficient method in the area of energy harvesting and also power generation systems. That is because of the simple construction (based on scale) and the power output capacity. First discovered in 1831 by Michael Faraday, electromagnetic induction system has a potential in generating electric current in a conductor within a magnetic field when either one of this factor experience a relative motion. Faraday's law indicates that the voltage or, also known as, electromotive force (EMF) is directly proportional to the rate of change of the magnetic flux linkage in the particular circuit, i.e.

$$V = -\frac{d\phi}{dt} \tag{4}$$

where V is denoted by the voltage generated or induced emf and $\emptyset$ is the flux linkage. Most of the generators consist of a coil of wire with multiple turns and permanent magnets to create the magnetic field. The voltage generated in *N* turns of coil, in this case, are shown in equation (5):

$$V = -\frac{d\Phi}{dt} = -N\frac{d\phi}{dt} \tag{5}$$

where Φ denotes the total flux linkage of the N turns of coil. It can also be approximated as, $N\phi$, which in this particular case, ϕ can be interpreted as the average flux linkage per turn. The general flux linkage for a multiple turn coil are comprised as the sum of the linkages for individual turns, i.e.

$$\Phi = \sum_{i=1}^{N} \int_{A_i} B \bullet dA \tag{6}$$

where *B* is the magnetic field flux density over the area of the *i*th turn. The integral part can be simplified to the product of the coil area, number of turns and the component of flux density perpendicular to the coil area in cases where the flux density are considered to be uniform over the area of the coil, as shown in equation (7):

$$\Phi = NBA\sin\alpha \tag{7}$$

where α is the angle between the coil area and the flux density direction. In our application, the rate of the coil cutting through the magnetic field is manipulated in order to generate current in the coil, which are placed in the disc (Beeby *et al.*, 2006; Priya & Inman, 2009). The electrical potential which can be generated by our designed power generator, can be generalized with the following equation (8):

$$V = NA\frac{dB}{dt}\sin\alpha \tag{8}$$

2.4 Summary

In this chapter the background literature on this project was reviewed. First, a general insight on LOD and other fluid propulsion techniques were presented. The advantage and disadvantage of each technique were highlighted. Through the comparison, LOD technique were highlighted and justified for the scope of this project. Following on the justification, the principles of LOD were described and passive / active modes in LOD were highlighted. The active mode applications on LOD was reviewed and power consumption of each method were justified. Current limitation of active mode were presented and the research problem were established. The research problem leads to the research objective of this thesis.

The following chapter describes the energy harvesting background and describes the mathematical equation for power generator design. First, the conversion mechanisms of energy harvesting were presented. This section describes the general conversion mechanism from kinetic energy to electrical power. Following on to that, a review on applications of suitable energy harvesting techniques on rotating environment were presented. From the comparison and analysis, the best energy harvesting technique for LOD was identified. The two best technique, which are the 1) Piezoelectric and 2) Electromagnetic Induction were reviewed and the mathematical derivation were described.

In general, the suitability for implementation of both energy harvesting techniques on LOD platform have been analyzed and it was concluded that the piezoelectric and electromagnetic induction conversion mechanism will be implemented on LOD for this project.

University of Malaya

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter describes the development of sustainable power generator on LOD in details. It is divided into three main sections which are 3.2) Experiment Setup, 3.3) Development of Piezoelectric Film Power Generator, and 3.4) Development of Electromagnetic Power Generator. The first section covers the general LOD fabrication technique before describing in detail on the LOD spin stand which is modified to accommodate the applications of both power generators. In the same section, the preliminary experiment to identify the power generation characteristic of piezoelectric film and electromagnetic system are described. Section 3.3 describes the development process and the experiment protocols for the piezoelectric film power generator. Section 3.4 covers the fabrication process and the experiment protocols of the electromagnetic power generator. Finally, in section 3.5, the methodology for the application of localized heating on disc is described. The general work flow of this work is illustrated in a flowchart in Figure 3.1.

University of Malaya

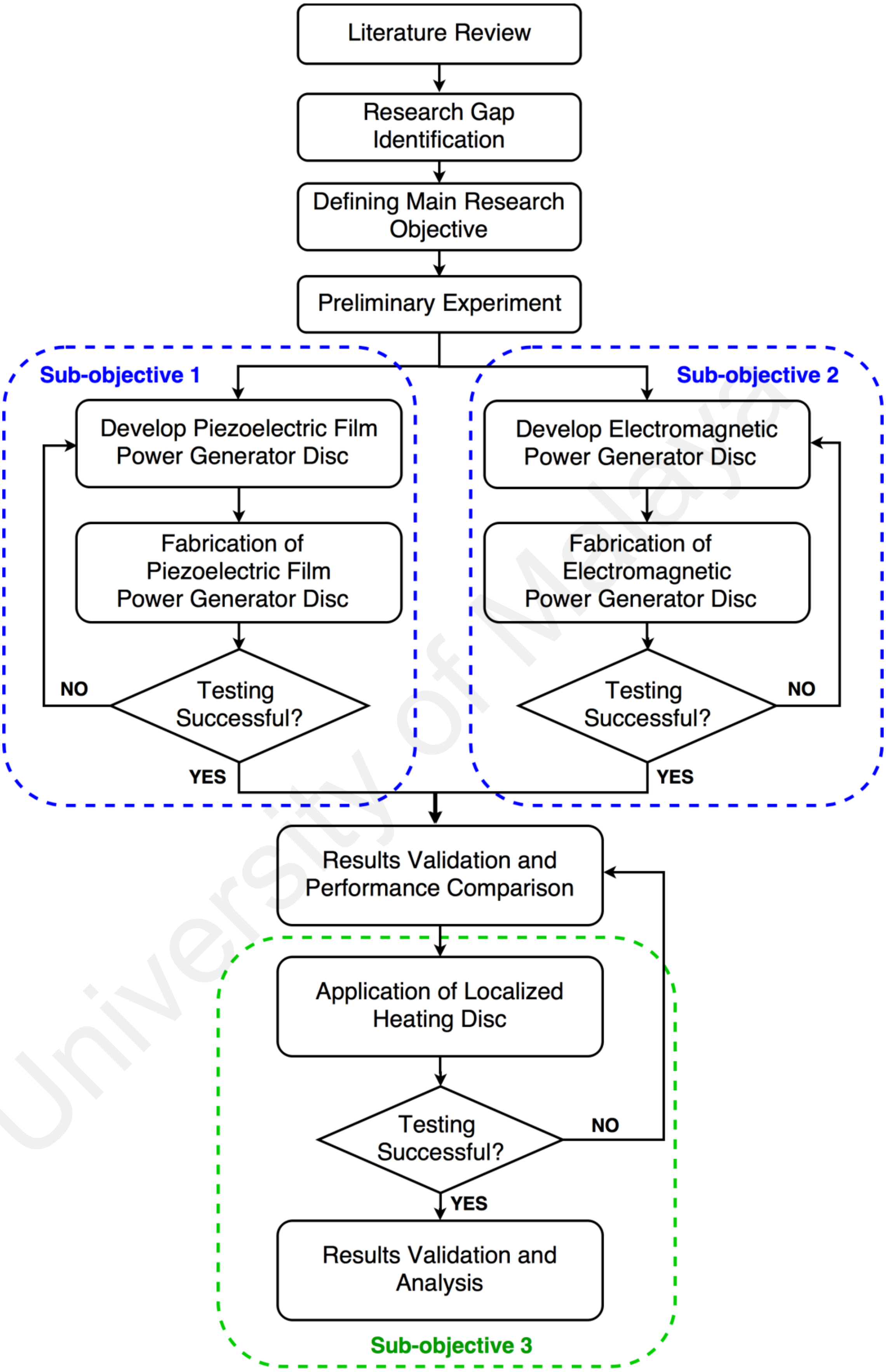

Figure 3.1: Flowchart of the overall methodology

University of Malaya

3.2 Experimental Setup

3.2.1 LOD Fabrication Technique

The discs are made of Polymethyl Methacrylate (PMMA) sheets and stacked onto each other using Pressure Sensitive Adhesive (PSA) material. There are three-layer disc and two-layer disc. The three-layer disc is made of 3 layers of PMMA, and 2 layers of PSA, meanwhile the two-layer disc is made of 2 layers of PMMA and a single layer of PSA. A Vision 2525 Computer-Numerical-Control (CNC) routing tool is used to engrave/cut these PMMA layers (Figure 3.2 (A)). For the PSA layer, PUMA X60 cutter plotter is used to cut based on the design (Figure 3.2 (B)).

The fabrication process of LOD is mainly divided into 4 steps. 1) Disc Design, 2) Disc Engraving/Cutting, 3) Cleaning, and 4) Binding. For the first part, which is the Disc Design, a Computer-Aided-Drawing (CAD) software is used to draw a 2D design on the disc by each layer. In this step, the dimensions are all made based on application. For the power generator disc, the design is based on the energy harvester and the components that need to be added on. The second step is basically uploading the CAD drawings into the CNC machine and fixing the tool tip based on the cutting or engraving size. The cleaning step is very important in order to ensure the fabricated layers do not have any debris and dust on it. The final step which is the binding step requires a custom-made aluminum jig with alignments to align each layers on top of each other. The PSA layer comes in between of each layer. Once the layers are all in place, the discs will be placed into a roller tool (refer to Figure 3.2(C)) to ensure the layers stick to each other well. Since the operation for the piezoelectric film based generator and electromagnetic induction based generator are different, the design and functionality are different. The fabrication of each disc will be carefully explained in section 3.3 (Piezoelectric Film Power Generator), 3.4 (Electromagnetic Induction Power Generator), and 3.5 (Application of Localized Heating).

University of Malaya

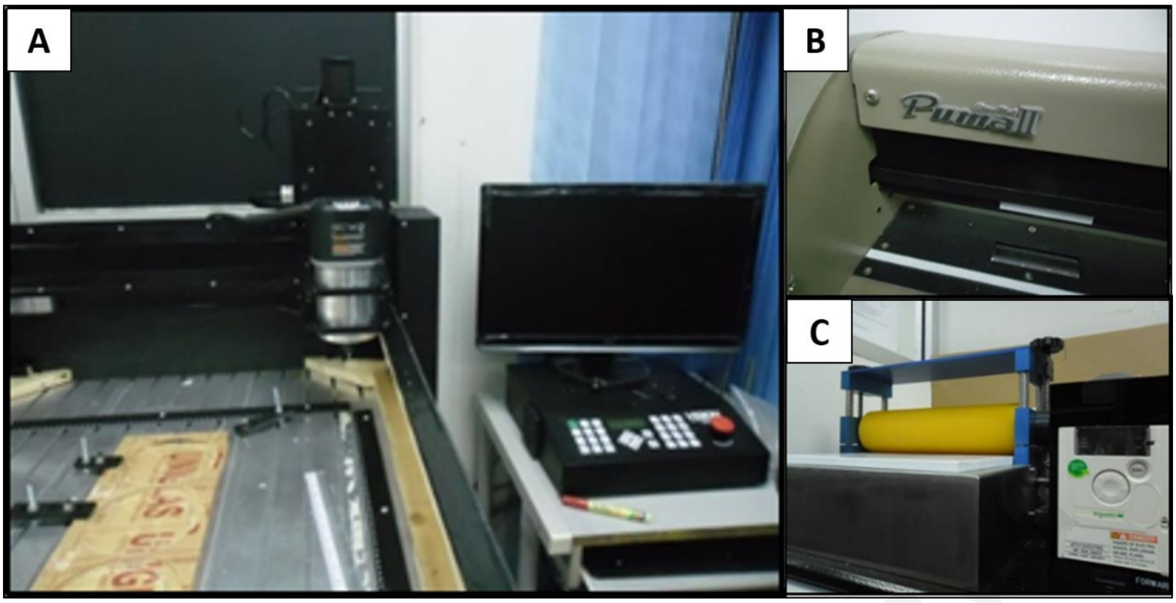

Figure 3.2: The equipment setup used for LOD fabrication
A) The CNC machine along with the controller unit (right) B) The PUMA cutter plotter for PSA cutting C) The compressor unit for final disc pressing.

3.2.2 LOD Spin Stand Enhancement

Each power generator method has different experiment protocols. However, both experiments are conducted using the same custom built LOD spin stand. In general, the LOD spin stand has a motorized module fixed on a solid platform and is controlled using a computer. The computer has a software as an interface to input the spinning profile and to observe the spinning speed of the disc. The general LOD spin stand is shown in Figure 3.3(A). In order to measure the voltage output from the power generators, additional configurations are needed. The piezoelectric film based generator disc requires a slip rails at the bottom of the disc to provide electrical connection with the moving disc (refer to Figure 3.3(B)), similar to slip-ring mechanism used for DEP on LOD application (Martinez-Duarte et al., 2010). The red and black crocodile clips shown at the edge of Figure 3.3(B) are the inputs to oscilloscope to measure the output waveform. The electromagnetic power generator disc has an on-disc wireless voltage meter to read and record the voltage generated while the disc is spinning. Besides that, the electromagnetic power generator also requires an array of permanent magnets to be installed on the spin

University of Malaya

stand. The installation of permanent magnets are shown in Figure 3.3(C). Implementation and detailed protocols will be described in the following sections.

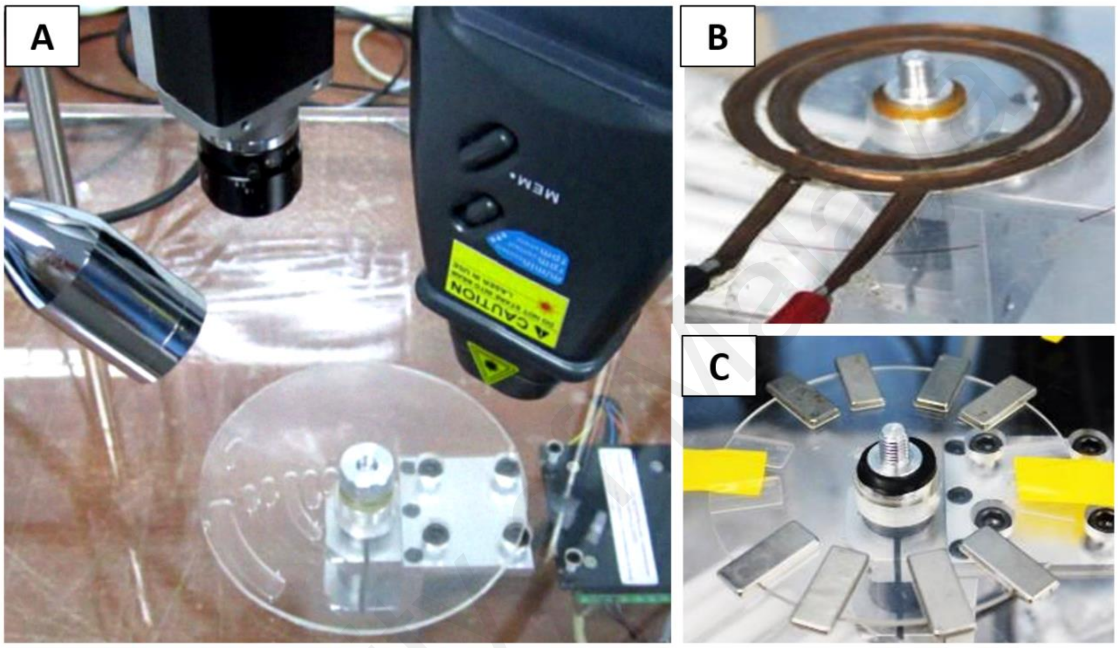

Figure 3.3: The general LOD Spin Stand Setup

A) The basic setup for LOD experiments. Adapted from (Ibrahim *et al.*, 2010) B) The copper rails for piezoelectric film power generator. C) The permanent magnets arrangement on the spin stand.

3.2.3 Preliminary Experiment for Identifying Power Generation Characteristic of Piezoelectric Film and Electromagnetic Induction Power Generator

In order to optimize the piezoelectric film based power generator, the characteristic of the piezoelectric film has to be validated. In this case, an experiment was modeled to investigate the optimum frequency for the piezoelectric film to generate maximum power output. A frequency switching circuit was develop to make an electromagnetic polarity switching system. The circuit are shown in detail in Figure 3.4. The system consists of two poles of soft iron with opposite polarity to switch turn upon the frequency set in the function generator (Figure 3.5). The switching frequency are determined by the function generator. The square wave from function generator drives the transistor which switches the MOSFET. The function generator outputs TTL level voltage to the switching circuit and the frequency is varied according to the desired frequency.

The same model of piezoelectric film with a piece of ferromagnetic material attached on the end of the film placed in the middle of the two soft iron rods. The distance of the rods, magnetic strength (current input to the solenoid) were fixed for the entire experiment. The peak-to-peak voltage (Vpp) generated at each step of 5 Hz (from 0 – 120 Hz) was recorded. The same experiment was conducted with the introduction of resistive load connected across the output terminals of the piezoelectric film. The resistors used were 10 kΩ, 100 kΩ, 1 MΩ, and 10 MΩ respectively.

University of Malaya

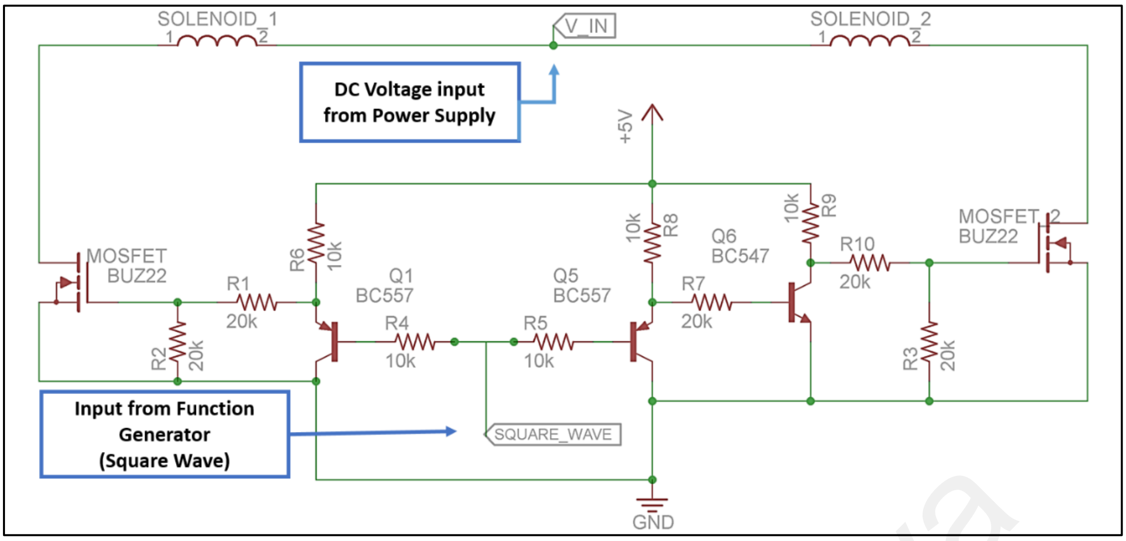

Figure 3.4: The Circuit Schematics of Vibration System.

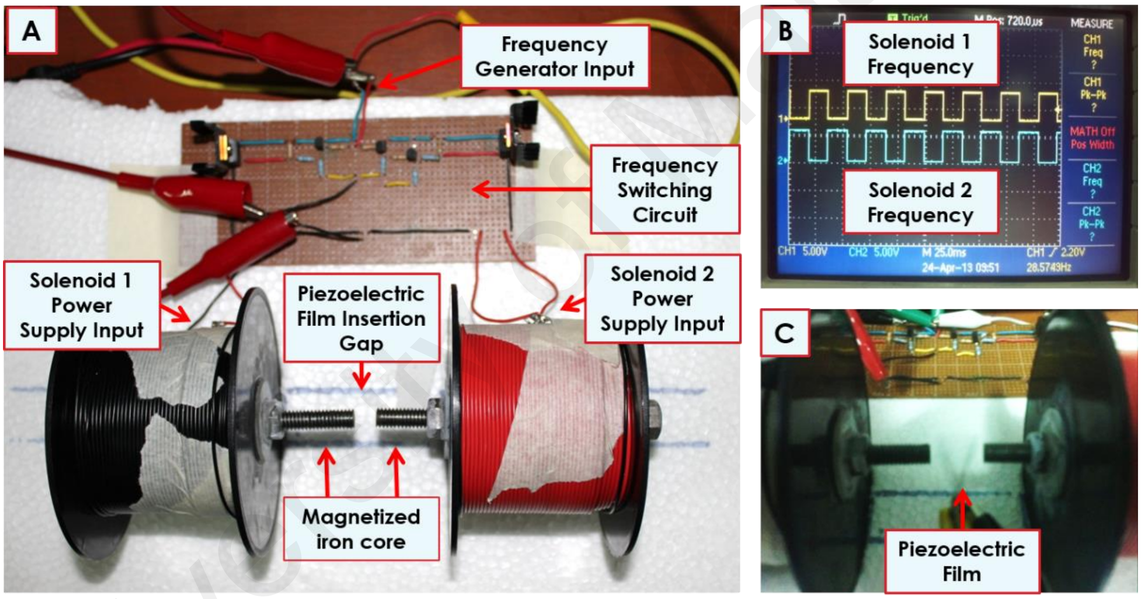

Figure 3.5: The Vibration System Setup for Preliminary Testing.
A) The picture of the complete setup and the connections. B) The difference of supply frequency phase is exactly 180 degrees. This changes the polarity of DC current supplied to the solenoids and induced the iron core. C) The vibrating piezoelectric film under test. The vibration frequency is controlled using a function generator.

3.3 Development of Piezoelectric Film based Power Generator Disc

Piezoelectric film based power generating disc consists of 3 layers: two layers of 2 mm PMMA and one layer of PSA. These three layers acted as the platform for the piezoelectric film (FS-2513P made of PROWAVE) slots. Materials used in the piezoelectric film are known as Polyvinylidene Fluoride (PVDF). The PSA layer comes in between of two PMMA layers to hold both layers to each other. Each rectifying circuit was implemented with an SMD type bridge rectifier (part no: HD01-T by DIODES INC) connected in parallel with a 22 µF capacitor (by RUBYCON) to rectify and smoothen the output voltage from each piezoelectric film. The breakout and conceptual image are detailed in Figure 3.6. The rectifying circuits were placed on the disc (Figure 3.6 (C)) and the piezoelectric film's electrodes were connected to the bridge rectifier once the piezoelectric film slotted on to the disc.

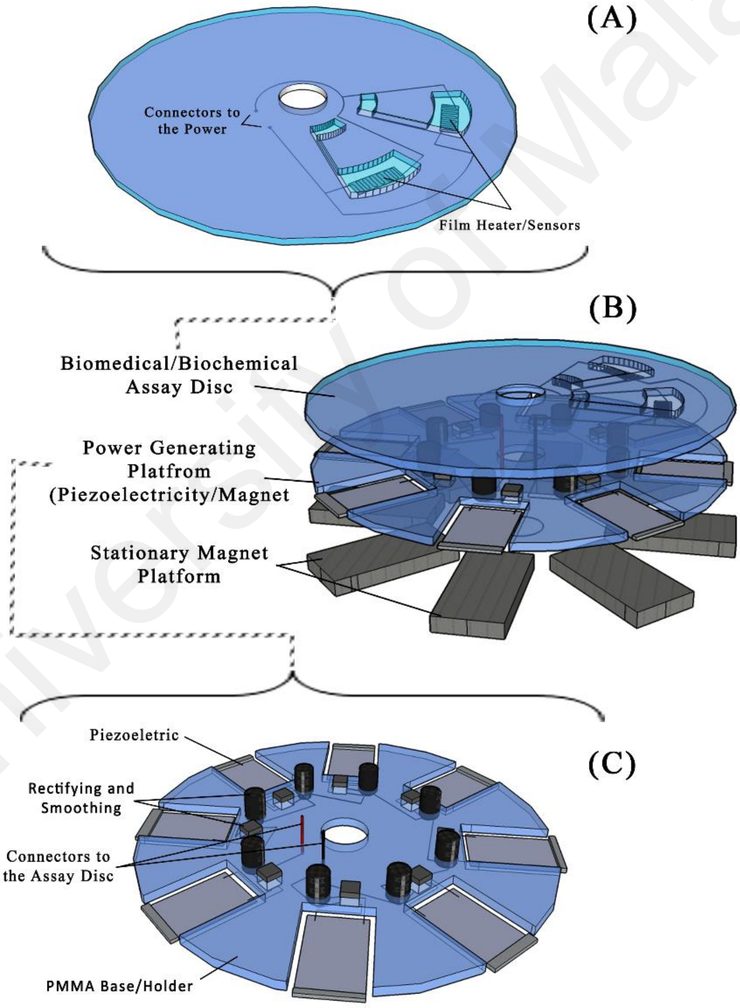

Figure 3.6: The conceptual and breakout diagram of

University of Malaya

3.3.1 Experiment Protocol of Piezoelectric Film Disc

Once the experiment to find the optimum frequency had been conducted, the application of the piezoelectric film on a disc platform was tested. Arrangement was made on the disc to fit six piezoelectric films which were connected in series. The output voltage from each film is supplied to individual rectifier coupled with a capacitor in parallel to rectify the generated AC voltage and smoothen to DC voltage. Since the natural vibration available during the spinning of the disc is not controllable, a method to externally induce the vibration was introduced. This was achieved by inducing the fluctuation of the film with a magnet on the film and on the stationary platform. The magnet was placed at the end of the film, outward from the disc center to optimize the bending of the film. The piezoelectric film holder provides support to the middle of the film and creates a distance for the deformation to occur. Another platform to establish a connection between the spinning piezoelectric film disc and the oscilloscope was placed directly under the disc. The stationary magnets were also placed on the same platform with a specific distance from the edge of the piezoelectric film on the disc to optimize the bending. The disc was spun with an increase of 10.47 rad/s (100RPM) for each 300 seconds up to 83.76 rad/s (800RPM).

3.4 Development of Electromagnetic based Power Generator Disc

The electromagnetic induction based power generator is made of a set of 6 coil stacks. Figure 3.7 illustrates the conceptual and breakout diagram of electromagnetic induction based power generator. A single coil stack is made of 1100 turns of SWG 36 polyurethane coated copper wire and wounded on a bobbin made of PMMA. Two layers of PMMA are designed to clamp 6 stacks which are angled 60˚ degree from the adjacent stack. The stationary magnets are fixed on the spin system with the magnets arranged according to the coil stack polarity (Figure 3.7 (A & B)).

University of Malaya

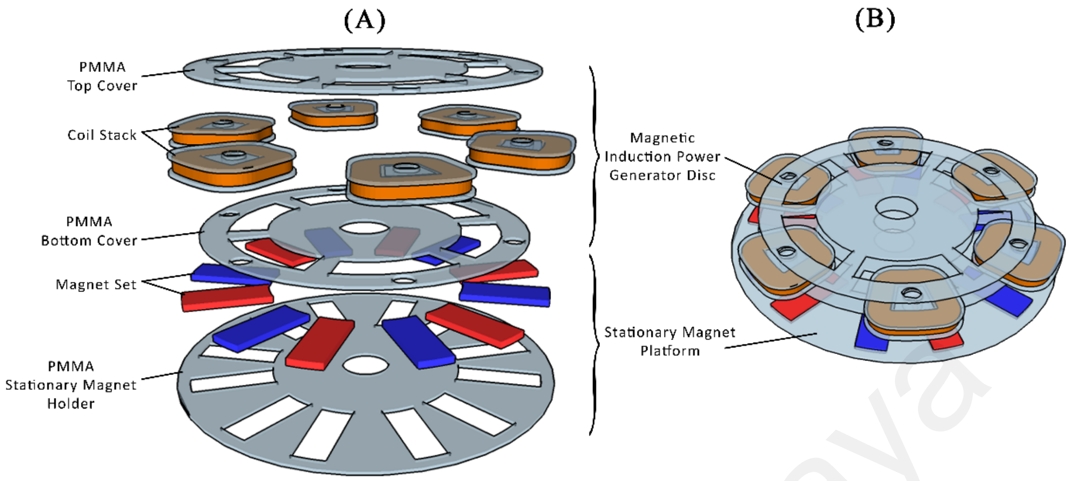

Figure 3.7: Conceptual and breakout diagram of electromagnetic induction based power generator disc.

3.4.1 Experiment Protocol of Electromagnetic Induction Disc

A wireless voltage meter was designed and implemented to measure the generated voltage from each coil and transmit the data to a remote computer. The wireless voltage meter was devised to ensure efficient data monitoring and to avoid unnecessary noise during experiment. A pair of ZigBee modules was used to establish the wireless communication and an ATMEGA328P microcontroller was used to read the analog voltage output from the coils. The schematic diagram are illustrated in Figure 3.8. This method provides better voltage measuring option compared to the rotor spin chunk system. The experiment was conducted by testing only a pair of coil stack instead of all 6 coil stacks to avoid excess of load applied to the spinning module's motor. The phase angle difference was also monitored by capturing voltages output from coil 1 and coil 2 simultaneously and then with coil 1 and coil 3 up to 6th coil. The wireless voltage meter had a limitation to only read voltage up to 3.96V. A voltage divider was introduced to measure voltage higher than 3.96V from the coil. This voltage divider also acts as a resistive load for the system for the power generation experiment.

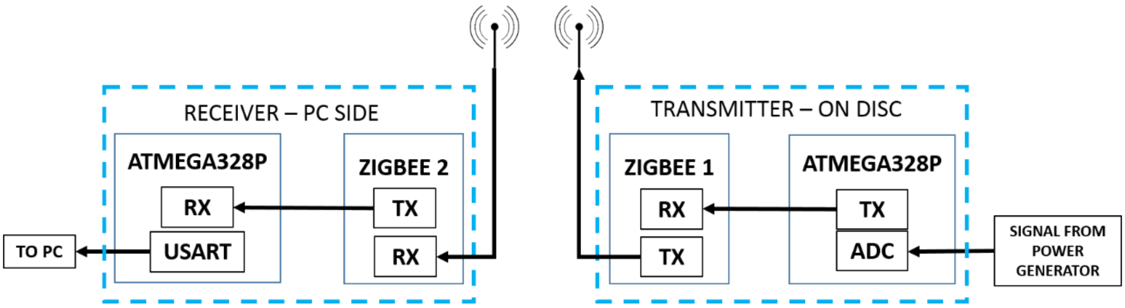

Figure 3.8: The schematic diagram of the wireless voltage measuring system

3.5 Application of Localized Heating and Wireless Temperature Monitoring on Disc

Based on the power generation capacity of both piezoelectric film disc and electromagnetic disc, the best suitor will be integrated with a localized heating disc to perform localized heating system on the disc.

The localized heating disc is made up of a heating element and a wireless temperature monitoring system. The heating element is made of 40 AWG Nickel Chromium wire with resistance of 555 Ω, insulated with Kapton film. To read the temperature, a digital temperature sensor (ADT7420) is embedded together with the heating element and connected to an ATMEGA328PU microcontroller. The temperature readings are sampled every 240 milliseconds. The digital temperature sensor and the microcontroller communicates through the Two-Wire-Interface (TWI) protocol. The program source code are included in Appendix A for further reference. In order to continuously monitor the heating during the operation, the microcontroller is interfaced with a Zigbee module to wirelessly transmit the temperature readings to another Zigbee module connected to a PC. The schematic diagram of this setup are illustrated in Figure 3.9.

The localized heating disc is mounted on top of the power generator disc. The power output from the power generator disc is directly connected to the heating element. To ensure undisrupted temperature monitoring, the microcontroller, temperature sensor and Zigbee module are powered by a Lithium Polymer battery during the whole operation.

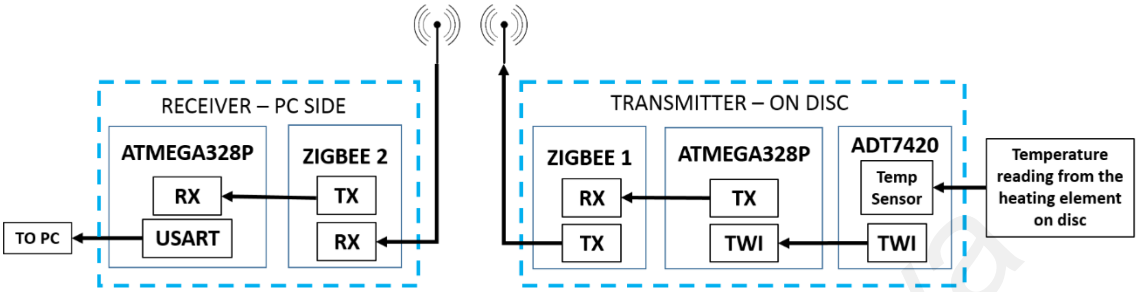

Figure 3.9: The schematic diagram of the wireless temperature monitoring system

University of Malaya

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents and discusses the results obtained in this research. The chapter includes the two final fabricated power generator discs. After that, for each power generator disc, the experimental results are presented and discussed. Based on the power generation capability of both power generator discs, the disc with higher power output is experimented with the localized heating disc. The results of the fabricated disc are presented. Finally, the results of localized heating systems are analyzed and presented.

4.2 Results of Piezoelectric Film based Power Generator

4.2.1 Setup of Piezoelectric Film based Power Generator Disc

In order to design the piezoelectric film based power generator, the actuation mechanism for the piezoelectric film has to be decided first. Actuation mechanism is how the piezoelectric film will undergo vibration and generate electricity. Several configuration were employed however the cantilever type vibration produces most prominent result. By this method, the deflection of the film can be optimized and controlled. Figure 4.1(A) illustrates the final fabricated piezoelectric film based power generator. The placement of rectifying and smoothing circuits is also shown. The experimental setup of the disc is shown in the Figure 4.1(B). Figure 4.1(C) shows the copper rails which provide electrical connections to the disc and the oscilloscope. Figure 4.1 (D-F) illustrate the deflection of the piezoelectric film as it nears the stationary magnet on the spin stand. The deflection occurs once every revolution of the disc, for each of the piezoelectric film. Another setup was employed to place 6 magnets instead of 1, however the attraction of the ferromagnetic material embedded on the film to the magnets overcomes the maximum allowable torque of the motor which stalls the spinning of the disc. With a single magnet, the vibrating frequency of the film is directly proportional to the spinning frequency of the disc.

University of Malaya

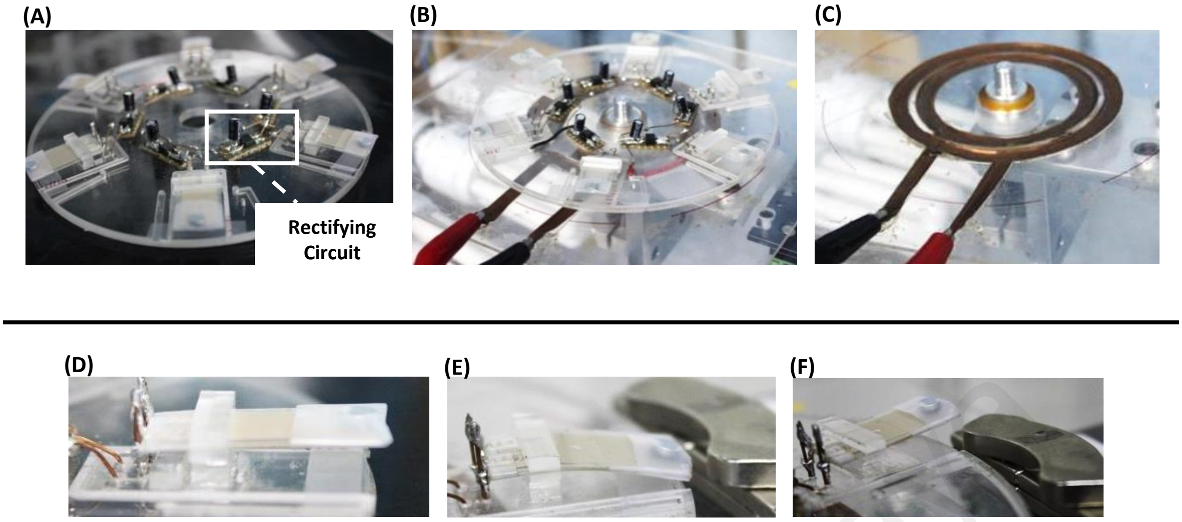

Figure 4.1: The Piezoelectric Disc and the Operation
(A) The piezoelectric film power generator disc fully assembled. (B) The experimental setup of the disc with connection to oscilloscope. (C) The copper rail/track which were placed at the bottom disc to read the generated voltage using the spinning. (D - F) The state of piezoelectric film's deformation when it passes by the stationary magnet.

4.2.2 Results for Power Generation of Piezoelectric Film based Power Generator

As a result of polarization and depolarization in the piezoelectric film when the film is deflected, alternating current (AC) is generated and recorded in voltage (V). Based on the preliminary experiment described in Section 3.3, the results of piezoelectric film power generation capacity are shown in Figure 4.2(A). It concludes four different power generation results using the same piezoelectric film, but with different resistive loads and vibration frequencies. The maximum power is observed to be in the range of 42-48 Hz. This also concludes the resonant frequency range of the film. Besides that, the resistive load effects are also shown in Figure 4.1(A). The maximum power was achieved with a resistive load of 1 MΩ. Based on the maximum power transfer theorem whereby in order to generate maximum power, the load resistance must be equal to the internal resistance of the system (Kong *et al.*, 2010; Shu *et al.*, 2006). This concludes that the piezoelectric film used for these experiments has high internal impedance.

University of Malaya

Based on the preliminary experiment, there are two main challenges in developing the piezoelectric film based power generator, 1) high internal impedance ~1MΩ, and 2) high frequency needed for high power generation (42-48Hz) relative to normal spinning speed range for LOD system (10-25Hz).

Besides that, the preliminary experiment also helps in designing the piezoelectric film power generator disc and the experimental setup. The final disc which was designed and fabricated according to the results of the preliminary experiments are shown in Figure 4.1(A). The experimental setup for the particular disc are shown in Figure 4.1(B-C). During the experiment, the disc was spun from 0 rad/s (0RPM) and increased by 1.047 rad/s (10RPM) every step until the maximum speed that the disc could endure. This was to test the stability of the disc while it spins. The disc spinning speed could not exceed 83.78 rad/s (800RPM) due to two main reasons, 1) the disc starts to wobble and 2) the spin stand motor's torque was limited and it stalls. After that, the disc was spun directly from 0 rad/s (0RPM) to 4 specified spinning speed which are 1) 10.47 rad/s (100RPM), 2) 20.94 rad/s (200RPM), 3) 41.88 rad/s (400RPM), 4) 62.83 rad/s (600RPM), and 7) 83.78 rad/s (800RPM). No resistive load was added for measuring however, the charging rate of the smoothing capacitor was observed. The reading was taken for 300 seconds using an oscilloscope connected to the copper rail on the spin stand (Figure 4.1(C)). The results are shown in Figure 4.2(B). It can be observed that, the increase in the spinning speed results in increase in the voltage measured across the smoothing capacitor. However, it requires a long settling time to reach the maximum voltage for each spinning speed. This is because of the very low charging current generated by the piezoelectric films to charge the capacitor.

University of Malaya

Looking closely at the result for 83.78 rad/s (800RPM) voltage generation curve in Figure 4.2(B), the charging current can be calculated based on the capacitor charging current equation shown in equation (9).

$$I = \frac{V_P}{R} e^{-t/RC} \tag{9}$$

where I is the charging current, V_P is the maximum voltage supplied to the capacitor, R is the internal resistance of the piezoelectric film, t is the instantaneous time in seconds, and C is the capacitance of the capacitor. The capacitor was charged maximum at 13V after 150 seconds and the measured internal resistance was 1.49MΩ. This results to a maximum achievable charging current of 8.792µA at 83.78 rad/s (800RPM).

Focusing on the maximum voltage for each spinning speed from Figure 4.2(B), an exponential fitted curve was made using least square method. The result is shown in Figure 4.2(C). Based on the maximum achievable charging current at 83.78 rad/s (800RPM), this figure shows the exponential increment of voltage as the spinning speed increase. In conclusion, to achieve higher charging current, higher spinning speed is required. Higher spinning speed contributes to higher frequency. However, the system is limited in this case since the disc wobbles and the limited torque range of the spin stand.

To meet these limitations, additional 5 permanent magnets were added and aligned at 60° degrees to each other from the center of the spin stand. Theoretically, these will increase the piezoelectric film's deflection 5 times more than the previous setup and results to higher vibration frequency. However, the experiment failed as the additional magnets assignment results to more torque to the spin stand's motor and stops spinning after 10.47 rad/s (100RPM). This is the result of the increased magnetic attraction force from the magnet to the ferromagnetic material embedded on the piezoelectric film.

University of Malaya

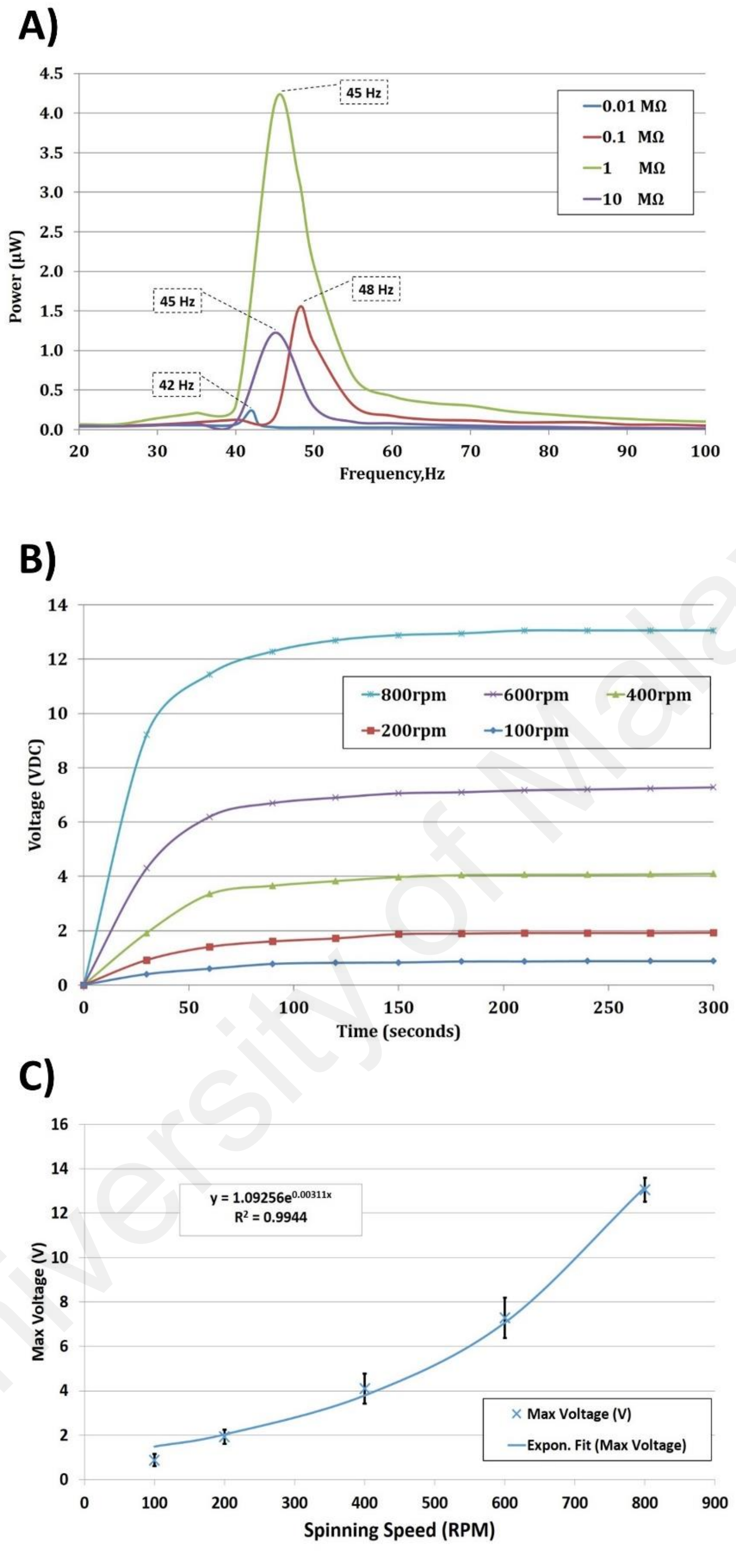

Figure 4.2: Results of Piezoelectric Film based power generator.
(A) The output power at different frequencies of vibration and resistive load. The spinning speed (RPM) when the maximum power measured is highlighted in the dotted box. (B) On the disc test: Variation of voltage output with spinning speed (RPM) for 300 seconds. No load applied to the system (C) On the disc test: Maximum voltage generated at each particular spinning rate (RPM). The solid line represents exponential fit to the experimental data with goodness of fit up to 0.9944 (n = 5).

University of Malaya

4.3 Results of Electromagnetic Induction Based Power Generator

4.3.1 Setup for Electromagnetic Induction Based Power Generator Disc

In order to design the electromagnetic induction power generator, the placement of the coils and magnetic flux source need to be determined. Since the idea is to provide power to the disc while spinning, the current generation system (the coils) should be embedded on the disc and the magnetic flux source (permanent magnets) should be as close as it can to the coils. In this design, the magnets are placed on the spin stand, beneath the power generator disc. The coils are embedded on a disc and placed horizontally against the magnets. The system setup is shown in Figure 4.3 (A). A close-up picture of the coil is shown in Figure 4.3(B) while the permanent magnets are shown in Figure 4.3(C). A different approach was taken for recording and measuring the voltage reading from the power generator with a wireless voltage meter which is explained in Section 3.6.1.

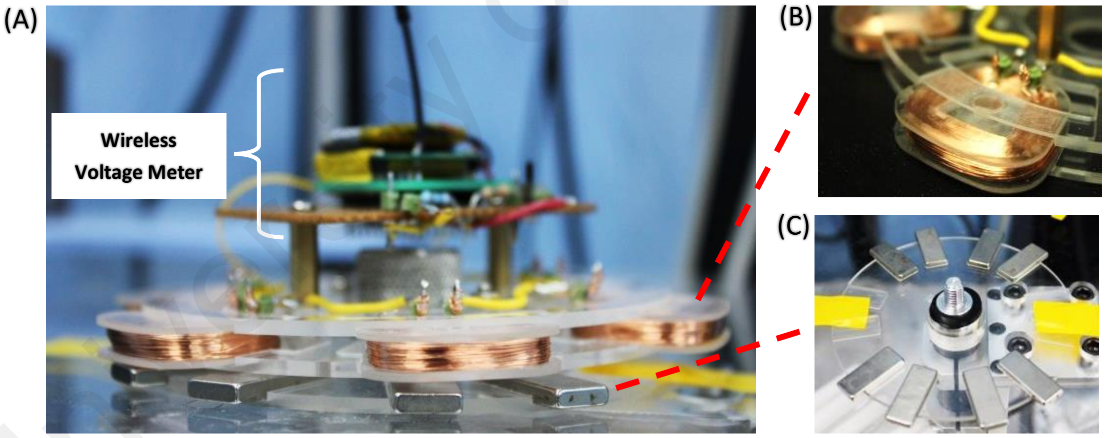

Figure 4.3: The Electromagnetic Induction disc and the Operation
(A) The fully assembled electromagnetic power generator disc placed on the LOD spin stand with a wireless voltage meter. (B) The enamel-coated copper coil stack embedded in the power generator disc. (C) The stationary magnet platform which are placed at the bottom disc.

University of Malaya

4.3.2 Results for Power Generation of Electromagnetic Induction Based Power Generator

Similar to the preliminary testing for piezoelectric film, the same setup was used for electromagnetic induction method. Since the setup explained and shown in Section 3.3 generates alternate electromagnetic polarity at the end of the poles, it was used to observe the power generation range for electromagnetic induction. The setup is able to generate approximately 0.47 mWb/s at the end of the poles during the experiment. The input frequency from the function generator was 15Hz. Two coil stacks were made with size similar to the pole's diameter but different coil diameter and number of turns. The coil stack was clamped in between of the poles and the output was connected to a 1kΩ resistive load. The output voltage across the load resistor is recorded and tabled in Table 4.1. The general relation between the numbers of turns with the power generated according to equation (4) has been proved. In this experiment, the coil diameter does not play any vital role however it corresponds to the space it consumes on the stack bobbin. That is why the number of turns was not made constant for the two different coil sizes.

Table 4.1: Power generated with different number of turns that is contributed by the diameter of the coil.

Coil Diameter (mm)	No of Turns*	Resistive Load (kΩ)	Voltage (Vrms)	Current (mAmp)	Power (nW)
0.2	300	1	0.144	0.144	20.736
0.5	80	1	0.056	0.056	3.136

**Note: Influenced by the diameter of copper coil used because the total space for coil on the disc is fixed.*

In general, the electromagnetic induction power generator is straight forward in terms of development compared to the piezoelectric film power generator. On top of that, the actuation mechanism can be achieved without contact. The current will be induced in the coils whenever there are relative displacement in the magnetic flux. Based on the power generator as shown in Figure 4.3, the current will be induced as the disc rotates over the

University of Malaya

permanent magnets. This scenario creates a relative magnetic flux change over the coils and current is generated. The higher the spinning speed is, the higher the magnetic flux change will take place. This correlation has been proved by comparing the spinning speed of the disc and the frequency of the current generated in the coil. This result is shown in Figure 4.4 (A). The six stationary permanent magnets on the spin stand contributes to six times of magnetic flux change for every single revolution.

The peak-to-peak voltage (Vpp) was measured at every 10.47 rad/s (100RPM) across a voltage divider which was embedded on the wireless voltage meter system. The voltage divider works as a resistive load and the voltage readings are shown in Figure 4.4 (B). Maximum voltage observed for a single coil stack was 5.3Vpp. The power was calculated from the readings and the results are shown in Figure 4.4(C). Output voltage from each stack was recorded to be able to generate up to 28 milliWatt and a total of 168 milliWatt at 157.07 rad/s (1500RPM). The 2 periods moving average curve describes the power generation trend for better understanding.

Focusing on the power generation graph shown in Figure 4.4(C), there are two main characteristics which can be observed. 1) High gradient in power generation from 10.47 rad/s (100RPM) to 62.83 rad/s (600RPM) and 2) Low gradient in power generation from 62.83 rad/s (600RPM) to 157.08 rad/s (1500RPM). The high gradient increases are observed to be linear and agree with equation (4). It also proves the hypothesis that the increase of magnetic flux change increases voltage generation as well as the power. However, the decrement in the gradient does not correlates with the linear equation. This is because of the diameter of the coil used. The diameter of coil is one of the important factor in designing power generators. Thinner coils are highly resistive and that is why the gradient decreases as the current flow increases. This is further supported as the coil stacks were observed to be slightly heated after the experiments. In general,

University of Malaya

electromagnetic induction based power generator proves to be better option for the localized heating system compared to the piezoelectric film based power generator.

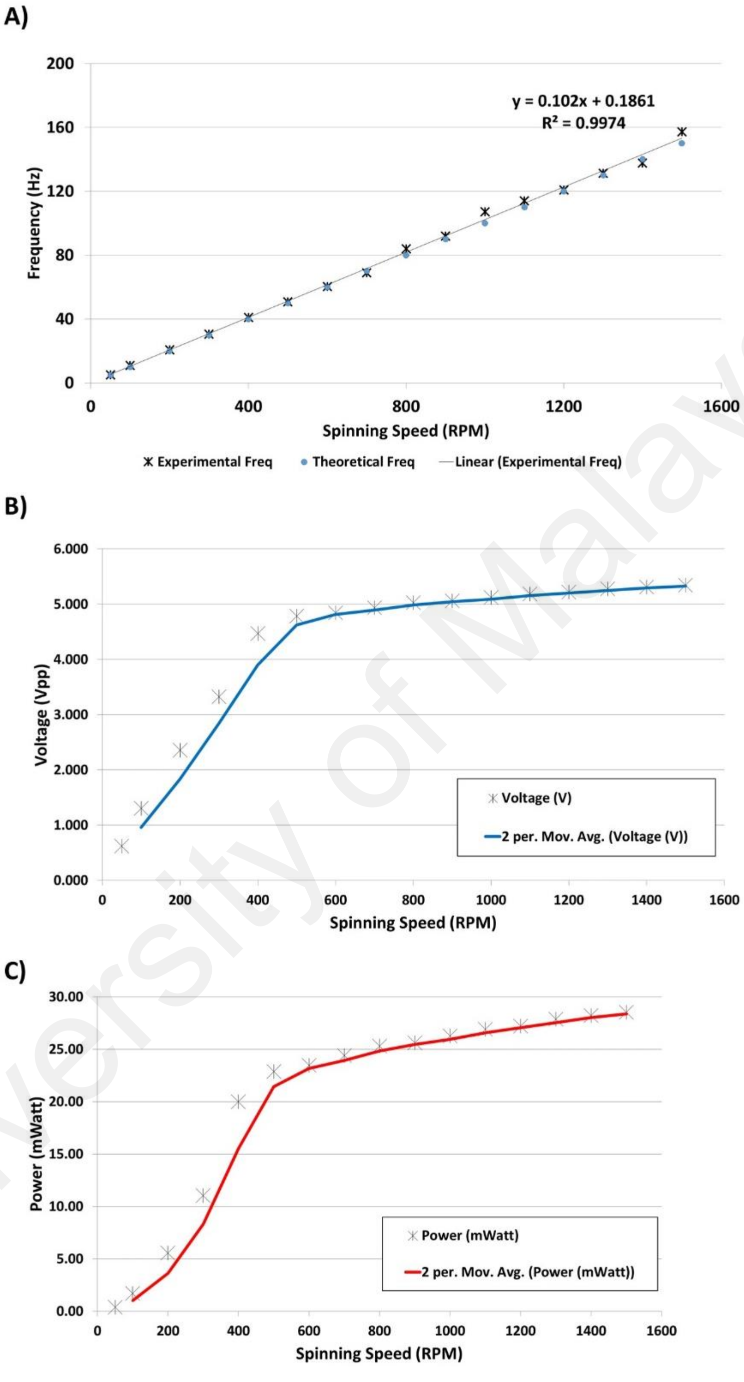

Figure 4.4: Results of Electromagnetic Induction based power generator. **(**A**)** Frequency of the voltage generated in comparison with the calculated frequency from the spinning speed of the disc. The black line represents the linear fit of theoretical and experimental data with a linear regression value of R^2 = 0.9974 (n=16). (B) The peak voltage generated from a single coil relative to the spinning speed (RPM). Output peak voltage illustrated by the moving average trend line of 2 periods. (C) Power generated relative to the spinning speed and the trend line illustrated with the moving average of 2 periods.

University of Malaya

4.4 Results of Applications of Power Generator for Localized Heating

4.4.1 Results of Applications of Power Generator for Localized Heating Disc

Based on the results from Section 4.2 and 4.3, electromagnetic induction power generator has better and higher power generation capability. This leads to the integration of localized heating system to be embedded to the electromagnetic induction power generator. Focusing only on the localized heating, a simple setup of heater and temperature monitoring system was fixed on a disc-like setup to be embedded on top of the electromagnetic induction power generator. The discs are shown in the Figure 4.5(A). The whole setup with the wireless temperature monitoring system is shown in Figure 4.5(B).

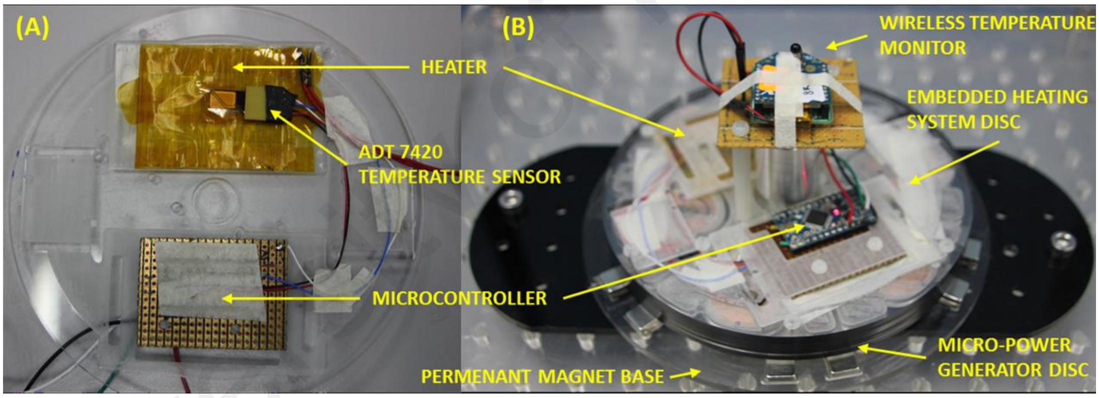

Figure 4.5: The Localized Heating and Wireless Temperature Monitoring Discs and Experimental Setup.

4.4.2 Results for Localized Heating on Disc

From the literature survey conducted in Section 2.2.3, most energy consuming applications in LOD are thermal energy required applications. The applications vary from incubations, nucleic assay amplification to valve actuation and pneumatic pumping systems. Focusing on these particular needs, the sustainable power generator on LOD implemented a novel localized heating system which was directly embedded on the disc. Besides that, it also offers wireless and direct-contact temperature measurement for

University of Malaya

precise controlling. This is another important breakthrough as the normal and conventional temperature measuring technique is by using non-contact laser thermometer, which is often not precise. A proof-of-concept heating approach was conducted by experimenting the achievable temperature as the spinning speed of the disc increased. The idea is that the spinning speed increases the power generation which will be directly supplied to the heater. The system however does not have any temperature controlling circuitry and power management system.

In this experiment, the disc was spun with increments of 10.47 rad/s (100RPM) at every 5 seconds until it reaches the intended speed. The intended speeds are 104.72 rad/s (1000RPM), 125.66 rad/s (1200RPM), 146.61 rad/s (1400RPM), 167.55 rad/s (1600RPM), 188.50 rad/s (1800RPM), 209.44 rad/s (2000RPM), and 230.38 (2200RPM). After the intended maximum speed, the speed is gradually decreased with decrement of 10.47 rad/s (100RPM) every 5 seconds. Before each heating cycles, the heating system is cooled at room temperature of 25°Celsius. The results of these experiment are shown in Figure 4.6. The maximum temperature achieved by the system is 58.62˚Celcius in 130 seconds at maximum spinning speed of 230.38 (2200RPM). Based on Table 2.3, this temperature meets the range required for wax valving, pneumatic pumping and incubation without any external equipment and power supply.

Looking at the heating curves in Figure 4.6, there is a significant difference in the heating up curve and cooling down curve. The gradient is higher during the heating but lower during the cooling. This is because of the continuous heating while the disc's speed is being reduced until it stops. Additional switching device can be used to cut off the current from the power generator if the disc needs to be cooled down faster.

University of Malaya

In general, this proof-of-concept demonstrates the possible solution for thermal energy based active applications on LOD. The temperature range suggests the possible application which can be achieved using the system.

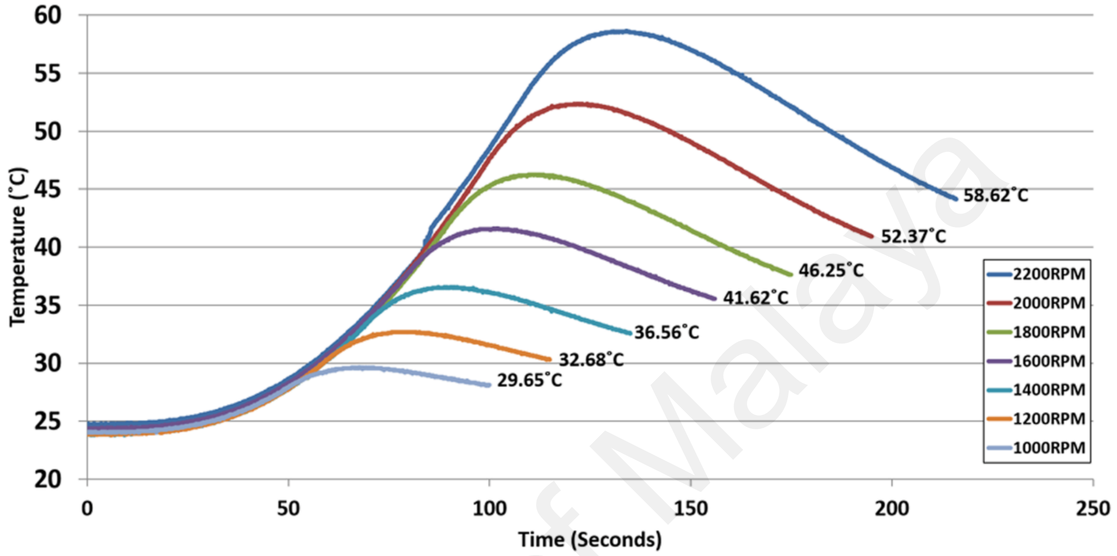

Figure 4.6: Heating and cooling characteristic of the embedded localized heating.

Shows the heating gradient based on the maximum spinning speed. The maximum temperature for each graph is denoted on the graph. The experiment was done in a closed chamber fixed on top of the spin test system.

University of Malaya

4.5 Summary

In this chapter, the experimental results of the piezoelectric film power generator and electromagnetic induction power generator were presented and evaluated. The characteristic of piezoelectric film were studied and a preliminary experiment to determine the frequency range to generate peak power output. The configuration and suitability of electromagnetic power generator were also discussed in order to optimize the output power. In summary, both piezoelectric film and electromagnetic induction power generator discs were successfully developed and tested on the LOD spin stand. The piezoelectric film based power generator with 6 films installed was capable of achieving up to 8.792µA at 83.78 rad/s (800RPM). On the other hand, the electromagnetic induction based power generator with 6 coils embedded was able to generate a total of 168 milliWatt at 157.08 rad/s (1500RPM).

Based on comparison of power generation from both technique, electromagnetic induction power generator was able to generate more power with stable output compared to piezoelectric film power generator. The electromagnetic induction power generator were then enhanced to be integrated with localized heating system. The power generated by the electromagnetic induction power generator was directly supplied to the heater embedded on the localized heating disc. The heating capacity of the system was tested at different spinning speed as the power generated will differ. Using custom-developed wireless temperature monitoring system, the heating was observed in real-time. The system was able to reach 58.62˚Celcius in 130 seconds at a maximum spinning speed of 230.38 rad/s (2200RPM). This temperature is in the range of most heat-consuming (refer Table 2.2 & 2.3) application on current LOD system. The objective of this thesis is achieved.

University of Malaya

CHAPTER 5: CONCLUSIONS

5.1 Introduction

This chapter presents the overall conclusion of this study and the specific contributions, limitations and the future works.

5.2 Conclusions

The energy harvesting-based power generator system for power consuming application in LOD using piezoelectricity and electromagnetic induction methods has been developed and tested successfully. The piezoelectric film power generator was developed using six pieces of piezoelectric film embedded on the disc. The mechanical vibration introduced to the films by a permanent magnet induces a voltage in the film. The results showed that it was capable of producing up to 8.792µA charging current at 83.78 rad/s (800RPM). For the electromagnetic induction power generator, six stacks of copper coil were embedded in the disc and spun over permanent magnets. This power generator was able to generate up to 168milliWatt at 157.08 rad/s (1500RPM). In comparison to the piezoelectric film based power generator, the electromagnetic induction power generator has a higher power generation capability for power consuming applications in LOD. It is based on the 1) higher power it can deliver compared to piezoelectric film power generator and 2) simplicity of the development of the power generator. The simplicity is an important factor in order to enhance the portability factor of LOD. Thus, the electromagnetic induction power generator was used for the biomedical application on LOD. The biomedical application in this research was the localized heating system which can be used for incubations and thermal cycling process in immunoassays applications.

The localized heating system was developed together with a wireless temperature monitoring system. The system was embedded on top of the electromagnetic induction power generator. The power generated from the power generator is directly supplied to the heater. The temperature readings are continuously monitored and the system was able to reach up to 58.62˚Celcius in 130seconds at a maximum spinning speed of 230.38 rad/s (2200RPM). Based on the review of current LOD system, the achieved temperature is in the range of the current temperature required in the LOD applications. This is the first energy harvesting approach in LOD field of research to solve the unavailability of power on the disc.

The major contribution of this research is the integration of energy harvesting techniques in LOD technology to provide power on the discs for energy consuming application on LOD. This research also presents a novel concept of localized heating using the power generated by the electromagnetic induction technique. It also provides a continuous, precise and direct-contact wireless temperature monitoring system for thermal-based LOD applications.

5.3 Recommendations for Future Work

The research has met and successfully accomplished all the specified objectives, however, the work can further be extended for more comprehensive solution. One of the recommended integration is a control mechanism for both power generator method. The power management system would have the capability to store the power for a short time and trigger release when there is a need for applications on LOD. Similar control system can be integrated to control the localized heating system. With a control mechanism, the heating can be controlled and actuated for different purposes and applications.

There are a number of significant recommendations and future work that can be employed to further advance the developed power generator:

University of Malaya

i. Introduce another application instead localized heating such as electrochemical (EC) analysis on LOD. The EC system can be employed to be powered by the power generator and using similar wireless temperature monitoring system, a wireless detection system can be introduced.
ii. Active micro-magnetic gas/liquid valving for complex LOD application. The micro-magnetic active valving can be powered by the power generator for gas sensing and analysis since it is one of the area which LOD have not ventured in yet.

University of Malaya

REFERENCES

Abi-Samra, K., Clime, L., Kong, L., Gorkin, R., Kim, T. H., Cho, Y. K., & Madou, M. (2011). Thermo-pneumatic pumping in centrifugal microfluidic platforms. *Microfluidics and nanofluidics*, 1-10.

Abi-Samra, K., Hanson, R., Madou, M., & Gorkin III, R. A. (2011). Infrared controlled waxes for liquid handling and storage on a CD-microfluidic platform. *Lab Chip, 11*(4), 723-726.

Abi-Samra, K., Kim, T.-H., Park, D.-K., Kim, N., Kim, J., Kim, H., . . . Madou, M. J. (2013). Electrochemical velocimetry on centrifugal microfluidic platforms. *Lab Chip*.

Aeinehvand, M. M., Ibrahim, F., Harun, S. W., Djordjevic, I., Hosseini, S., Rothan, H. A., . . . Madou, M. J. (2015). Biosensing enhancement of dengue virus using microballoon mixers on centrifugal microfluidic platforms. *Biosensors and Bioelectronics, 67*, 424-430.

Al-Faqheri, W., Ibrahim, F., Thio, T. H. G., Moebius, J., Joseph, K., Arof, H., & Madou, M. (2013). Vacuum/Compression Valving (VCV) Using Parrafin-Wax on a Centrifugal Microfluidic CD Platform. *PLoS ONE, 8*(3), e58523. doi:10.1371/journal.pone.0058523

Amasia, M., Cozzens, M., & Madou, M. J. (2012). Centrifugal microfluidic platform for rapid PCR amplification using integrated thermoelectric heating and ice-valving. *Sensors and Actuators B: Chemical, 161*(1), 1191-1197.

Amirtharajah, R., & Chandrakasan, A. P. (1998). Self-powered signal processing using vibration-based power generation. *Solid-State Circuits, IEEE Journal of, 33*(5), 687-695.

Anton, S. R., & Sodano, H. A. (2007). A review of power harvesting using piezoelectric materials (2003–2006). *Smart materials and Structures, 16*(3), R1.

Beeby, S. P., Tudor, M. J., & White, N. M. (2006). Energy harvesting vibration sources for microsystems applications. *Measurement Science & Technology, 17*(12), R175-R195. doi:Doi 10.1088/0957-0233/17/12/R01

Carlson, C. P., Schlichting, A. D., Ouellette, S., Farinholt, K., & Park, G. (2011). Energy harvesting to power sensing hardware onboard wind turbine blade *Structural Dynamics and Renewable Energy, Volume 1* (pp. 291-304): Springer.

Chen, Q., & Payne, P. (1995). Industrial applications of piezoelectric polymer transducers. *Measurement Science and Technology, 6*(3), 249.

Cho, Y. K., Lee, J. G., Park, J. M., Lee, B. S., Lee, Y., & Ko, C. (2007). One-step pathogen specific DNA extraction from whole blood on a centrifugal microfluidic device. *Lab Chip, 7*(5), 565-573.

University of Malaya

Conrad, S. D. (2007). *Development of an inertial generator for embedded applications in rotating environments.* Massachusetts Institute of Technology.

Czilwik, G., Messinger, T., Strohmeier, O., Wadle, S., von Stetten, F., Paust, N., . . . Niittymäki, J. (2015). Rapid and fully automated bacterial pathogen detection on a centrifugal-microfluidic LabDisk using highly sensitive nested PCR with integrated sample preparation. *Lab on a Chip, 15*(18), 3749-3759.

Delgado, S. M. T., Kinahan, D. J., Sandoval, F. S., Julius, L. A. N., Kilcawley, N. A., Ducree, J., & Mager, D. (2016). Fully automated chemiluminescence detection using an electrified-Lab-on-a-Disc (eLoaD) platform. *Lab on a Chip, 16*(20), 4002-4011. doi:10.1039/C6LC00973E

Erturk, A., & Inman, D. J. (2011). *Piezoelectric energy harvesting*: John Wiley & Sons.

Focke, M., Stumpf, F., Faltin, B., Reith, P., Bamarni, D., Wadle, S., . . . Francois, P. (2010). Microstructuring of polymer films for sensitive genotyping by real-time PCR on a centrifugal microfluidic platform. *Lab Chip, 10*(19), 2519-2526.

Goldfarb, M., & Jones, L. D. (1999). On the Efficiency of Electric Power Generation With Piezoelectric Ceramic. *Journal of Dynamic Systems, Measurement, and Control, 121*(3), 566-571. doi:10.1115/1.2802517

Gorkin, R., Park, J., Siegrist, J., Amasia, M., Lee, B. S., Park, J. M., . . . Cho, Y. K. (2010). Centrifugal microfluidics for biomedical applications. *Lab Chip, 10*(14), 1758-1773.

Gu, L., & Livermore, C. (2010). Passive self-tuning energy harvester for extracting energy from rotational motion. *Applied Physics Letters, 97*(8), 081904.

Harrison, D., Fan, Z., Fluri, K., & Seiler, K. (1994). *Integrated electrophoresis systems for biochemical analyses.* Paper presented at the Solid-State Sensor and Actuator Workshop.

Harsányi, G. (2000). Polymer films in sensor applications: a review of present uses and future possibilities. *Sensor Review, 20*(2), 98-105.

Henderson, B., Kinahan, D. J., & Ducrée, J. (2016). The Centrifugal Microfluidic: Lab-on-a-Disc Platform. In C. K. Dixit & A. Kaushik (Eds.), *Microfluidics for Biologists: Fundamentals and Applications* (pp. 115-144). Cham: Springer International Publishing.

Höfflin, J., Delgado, S. M. T., Sandoval, F. S., Korvink, J. G., & Mager, D. (2015). Electrifying the disk: a modular rotating platform for wireless power and data transmission for Lab on a disk application. *Lab on a Chip, 15*(12), 2584-2587.

Hu, Y., Lin, L., Zhang, Y., & Wang, Z. L. (2012). Replacing a battery by a nanogenerator with 20 V output. *Advanced Materials, 24*(1), 110-114.

Hu, Y., Xu, C., Zhang, Y., Lin, L., Snyder, R. L., & Wang, Z. L. (2011). A nanogenerator for energy harvesting from a rotating tire and its application as a self-powered

University of Malaya

pressure/speed sensor. *Adv Mater*, *23*(35), 4068-4071. doi:10.1002/adma.201102067

Ibrahim, F., Nozari, A. A., Jahanshahi, P., Soi, N., Rahman, N. A., Dawal, S. Z. M., . . . Madou, M. (2010). *Analysis and experiment of centrifugal force for microfluidic ELISA CD platform.* Paper presented at the Biomedical engineering and sciences (IECBES), 2010 IEEE EMBS conference on.

Jorgenson, J. W., & Guthrie, E. J. (1983). Liquid chromatography in open-tubular columns: theory of column optimization with limited pressure and analysis time, and fabrication of chemically bonded reversed-phase columns on etched borosilicate glass capillaries. *Journal of Chromatography A, 255*, 335-348.

Joseph, K., Ibrahim, F., Cho, J., Thio, T. H. G., Al-Faqheri, W., & Madou, M. (2015). Design and Development of Micro-Power Generating Device for Biomedical Applications of Lab-on-a-Disc. *PLoS ONE, 10*(9), e0136519. doi:10.1371/journal.pone.0136519

Joyce, B. S. (2011). Development of an electromagnetic energy harvester for monitoring wind turbine blades.

Kazemzadeh, A., Ganesan, P., Ibrahim, F., He, S., & Madou, M. J. (2013). The Effect of Contact Angles and Capillary Dimensions on the Burst Frequency of Super Hydrophilic and Hydrophilic Centrifugal Microfluidic Platforms, a CFD Study. *PLoS ONE, 8*(9), e73002. doi:10.1371/journal.pone.0073002

Khameneifar, F., Moallem, M., & Arzanpour, S. (2011). Modeling and analysis of a piezoelectric energy scavenger for rotary motion applications. *Journal of vibration and acoustics, 133*(1), 011005.

Kim, H., Kim, J.-H., & Kim, J. (2011). A review of piezoelectric energy harvesting based on vibration. *International Journal of Precision Engineering and Manufacturing, 12*(6), 1129-1141. doi:10.1007/s12541-011-0151-3

Kim, H., Tadesse, Y., Priya, S., & Inman, D. (2009). Piezoelectric energy harvesting. *Energy Harvesting Technologies*, *1*, 3-39.

Kong, N., Ha, D. S., Erturk, A., & Inman, D. J. (2010). Resistive impedance matching circuit for piezoelectric energy harvesting. *Journal of Intelligent Material Systems and Structures*, *21*(13), 1293-1302.

Lee, C.-K., & Moon, F. C. (1990). Modal sensors/actuators. *Journal of applied mechanics*, *57*(2), 434-441.

Li, T., Fan, Y., Cheng, Y., & Yang, J. (2013). An electrochemical Lab-on-a-CD system for parallel whole blood analysis. *Lab on a Chip, 13*(13), 2634-2640. doi:10.1039/C3LC00020F

Madou, M., Zoval, J., Jia, G., Kido, H., Kim, J., & Kim, N. (2006). Lab on a CD. *Annu Rev Biomed Eng, 8*, 601-628. doi:10.1146/annurev.bioeng.8.061505.095758

University of Malaya

Madou, M. J. (2002). *Fundamentals of microfabrication: the science of miniaturization*: CRC press.

Manla, G., White, N., & Tudor, J. (2009). *Harvesting energy from vehicle wheels.* Paper presented at the Solid-State Sensors, Actuators and Microsystems Conference, 2009. TRANSDUCERS 2009. International.

Martinez-Duarte, R., Gorkin, R. A., 3rd, Abi-Samra, K., & Madou, M. J. (2010). The integration of 3D carbon-electrode dielectrophoresis on a CD-like centrifugal microfluidic platform. *Lab Chip, 10*(8), 1030-1043. doi:10.1039/b925456k

Miyazaki, S.-i., Kawai, T., & Araragi, M. (1991). *A piezo-electric pump driven by a flexural progressive wave.* Paper presented at the Micro Electro Mechanical Systems, 1991, MEMS'91, Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots. IEEE.

Priya, S., & Inman, D. J. (2009). *Energy harvesting technologies* (Vol. 21): Springer.

Roundy, S., Wright, P. K., & Rabaey, J. (2003). A study of low level vibrations as a power source for wireless sensor nodes. *Computer communications, 26*(11), 1131-1144.

Roundy, S. J. (2003). *Energy scavenging for wireless sensor nodes with a focus on vibration to electricity conversion.* University of California, Berkeley.

Shu, Y., & Lien, I. (2006). Analysis of power output for piezoelectric energy harvesting systems. *Smart materials and structures, 15*(6), 1499.

Smith, S., Mager, D., Perebikovsky, A., Shamloo, E., Kinahan, D., Mishra, R., . . . Ducrée, J. (2016). CD-Based Microfluidics for Primary Care in Extreme Point-of-Care Settings. *Micromachines, 7*(2), 22.

Smolorz, S., & Grill, W. (1996). Focusing PVDF transducers for acoustic microscopy. *Journal of Research in Nondestructive Evaluation, 7*(4), 195-201.

Sodano, H. A., Inman, D. J., & Park, G. (2004). A review of power harvesting from vibration using piezoelectric materials. *Shock and Vibration Digest, 36*(3), 197-206.

Thio, T. H. G., Ibrahim, F., Al-Faqheri, W., Moebius, J., Khalid, N. S., Soin, N., . . . Madou, M. (2013). Push pull microfluidics on a multi-level 3D CD. *Lab on a Chip, 13*(16), 3199-3209. doi:10.1039/C3LC00004D

Thio, T. H. G., Soroori, S., Ibrahim, F., Al-Faqheri, W., Soin, N., Kulinsky, L., & Madou, M. (2013). Theoretical development and critical analysis of burst frequency equations for passive valves on centrifugal microfluidic platforms. *Medical & biological engineering & computing, 51*(5), 525-535.

Toh, T. T., Bansal, A., Hong, G., Mitcheson, P. D., Holmes, A. S., & Yeatman, E. M. (2007). Energy harvesting from rotating structures. *Technical Digest PowerMEMS 2007 (Freiburg, Germany, 28–29 November 2007)*, 327-330.

University of Malaya

Toh, T. T., Mitcheson, P. D., Holmes, A. S., & Yeatman, E. M. (2008). A continuously rotating energy harvester with maximum power point tracking. *Journal of Micromechanics and Microengineering*, *18*(10), 104008.

Toh, T. T., Mitcheson, P. D., & Yeatman, E. M. (2008). Continuously rotating energy harvester with improved power density. *PowerMEMS, Sendai, Japan*.

Torres, E. O., & Rincón-Mora, G. A. (2006). *Electrostatic energy harvester and Li-Ion charger circuit for micro-scale applications.* Paper presented at the Circuits and Systems, 2006. MWSCAS'06. 49th IEEE International Midwest Symposium on.

Wang, Y.-J., Chen, C.-D., & Sung, C.-K. (2010). Design of a frequency-adjusting device for harvesting energy from a rotating wheel. *Sensors and Actuators A: Physical, 159*(2), 196-203.

University of Malaya

LIST OF PUBLICATIONS AND PAPERS PRESENTED

The following research papers has been published in ISI journals towards fulfilment of the research objective:

a. Joseph K, Ibrahim F, Cho J, Thio THG, Al-Faqheri W, Madou M (2015). Design and Development of Micro-Power Generating Device for Biomedical Applications of Lab-on-a-Disc. PLoS ONE 10(9): e0136519. doi:10.1371/journal.pone.0136519. (JCR 2014 ISI Q1, Impact Factor: 3.234).

PLOS | ONE

RESEARCH ARTICLE

Design and Development of Micro-Power Generating Device for Biomedical Applications of Lab-on-a-Disc

Karunan Joseph[1,2], Fatimah Ibrahim[1,2]*, Jongman Cho[1,2,3], Tzer Hwai Gilbert Thio[1,2,4], Wisam Al-Faqheri[1,2], Marc Madou[1,5,6]

1 Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia, **2** Centre for Innovations in Medical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia, **3** Department of Biomedical Engineering, Inje University, Gimhae, South Korea, **4** Faculty of Science, Technology, Engineering and Mathematics, INTI International University, Persiaran Perdana BBN, Putra Nilai, Nilai, Negeri Sembilan, Malaysia, **5** Department of Biomedical Engineering, University of California Irvine, Irvine, California, United States of America, **6** Department of Mechanical and Aerospace Engineering, University of California Irvine, Irvine, California, United States of America

* fatimah@um.edu.my

CrossMark
click for updates

OPEN ACCESS

Citation: Joseph K, Ibrahim F, Cho J, Thio THG, Al-Faqheri W, Madou M (2015) Design and Development of Micro-Power Generating Device for Biomedical Applications of Lab-on-a-Disc. PLoS ONE 10(9): e0136519. doi:10.1371/journal.pone.0136519

Editor: Dario Pisignano, Università degli Studi del Salento, ITALY

Received: October 24, 2014

Accepted: August 5, 2015

Published: September 30, 2015

Copyright: © 2015 Joseph et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the paper.

Funding: This research is supported by Fundamental Research Grant Scheme (FRGS: FP042-2013B) and University of Malaya Research Grant (UMRG: RG009A-13AET). Fatimah Ibrahim would like to acknowledge Yayasan Sultan Iskandar Johor Foundation for funding the Special Equipment Grant. Marc Madou acknowledges support of the National Institute of Health (grant 1 R01 AI089541-01).

Abstract

The development of micro-power generators for centrifugal microfluidic discs enhances the platform as a green point-of-care diagnostic system and eliminates the need for attaching external peripherals to the disc. In this work, we present micro-power generators that harvest energy from the disc's rotational movement to power biomedical applications on the disc. To implement these ideas, we developed two types of micro-power generators using piezoelectric films and an electromagnetic induction system. The piezoelectric-based generator takes advantage of the film's vibration during the disc's rotational motion, whereas the electromagnetic induction-based generator operates on the principle of current generation in stacks of coil exposed to varying magnetic flux. We have successfully demonstrated that at the spinning speed of 800 revolutions per minute (RPM) the piezoelectric film-based generator is able to produce up to 24 microwatts using 6 sets of films and the magnetic induction-based generator is capable of producing up to 125 milliwatts using 6 stacks of coil. As a proof of concept, a custom made localized heating system was constructed to test the capability of the magnetic induction-based generator. The heating system was able to achieve a temperature of 58.62°C at 2200 RPM. This development of lab-on-a-disc micro power generators preserves the portability standards and enhances the future biomedical applications of centrifugal microfluidic platforms.

Introduction

In the past decade, various researchers have shown interest in developing biochemical- and biological/medical- based sensors in an effort to perform assay integration on the lab-on-a-disc platform, also known as the centrifugal microfluidic disc platform [1–3]. The lab-on-a-disc platform has potential to emerge as a miniaturized and automated portable diagnostic tool in point-of-care applications [4–7].

PLOS ONE | DOI:10.1371/journal.pone.0136519 September 30, 2015 1 / 16

b. Al-Faqheri W, Ibrahim F, Thio THG, Moebius J, Joseph K, Arof H, et al. (2013). Vacuum/Compression Valving (VCV) Using Parrafin-Wax on a Centrifugal Microfluidic CD Platform. PLoS ONE 8(3): e58523. doi:10.1371/journal.pone.0058523. (JCR 2014 ISI Q1, Impact Factor: 3.234).

OPEN ACCESS Freely available online PLOS | ONE

Vacuum/Compression Valving (VCV) Using Parrafin-Wax on a Centrifugal Microfluidic CD Platform

Wisam Al-Faqheri[1], Fatimah Ibrahim[1]*, Tzer Hwai Gilbert Thio[1], Jacob Moebius[1,3], Karunan Joseph[1], Hamzah Arof[2], Marc Madou[1,3,4,5]

1 Medical Informatics and Biological Micro-electro-mechanical Systems Specialized Laboratory, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia, 2 Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia, 3 Department of Biomedical Engineering, University of California Irvine, Irvine, United States of America, 4 Department of Mechanical and Aerospace Engineering, University of California Irvine, Irvine, United States of America, 5 Ulsan National Institute of Science and Technology, World Class University, Ulsan, South Korea

Abstract

This paper introduces novel vacuum/compression valves (VCVs) utilizing paraffin wax. A VCV is implemented by sealing the venting channel/hole with wax plugs (for normally-closed valve), or to be sealed by wax (for normally-open valve), and is activated by localized heating on the CD surface. We demonstrate that the VCV provides the advantages of avoiding unnecessary heating of the sample/reagents in the diagnostic process, allowing for vacuum sealing of the CD, and clear separation of the paraffin wax from the sample/reagents in the microfluidic process. As a proof of concept, the microfluidic processes of liquid flow switching and liquid metering is demonstrated with the VCV. Results show that the VCV lowers the required spinning frequency to perform the microfluidic processes with high accuracy and ease of control.

Citation: Al-Faqheri W, Ibrahim F, Thio THG, Moebius J, Joseph K, et al. (2013) Vacuum/Compression Valving (VCV) Using Parrafin-Wax on a Centrifugal Microfluidic CD Platform. PLoS ONE 8(3): e58523. doi:10.1371/journal.pone.0058523

Editor: Arum Han, Texas A&M University, United States of America

Received November 20, 2012; **Accepted** February 5, 2013; **Published** March 11, 2013

This is an open-access article, free of all copyright, and may be freely reproduced, distributed, transmitted, modified, built upon, or otherwise used by anyone for any lawful purpose. The work is made available under the Creative Commons CC0 public domain dedication.

Funding: This research was financially supported by University of Malaya, Ministry of Higher Education High Impact Research (UM/HIR/MOHE/ENG/05), and University of Malaya Research Grant (UMRG: RG023/09AET). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors would like to acknowledge Prof. Dr. Noorsaadah Abd Rahman from Department of Chemistry, Faculty of Science, University of Malaya and her grant "Hitsto-Lead: Designing Dengue Virus Inhibitors, National Biotechnology Directorate (NBD) Initiative-Malaysian Institute of Pharmaceuticals and Nutraceuticals (IPharm),Ministry of Science, Technology and Innovation (MOSTI IPHARM 53-02-03-1049)" for partially sponsoring the initial set-up of the CD Spin Test System. MM also acknowledges support of WCU (World Class University) program (R32-2008-000-20054-0) through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: fatimah@um.edu.my

Introduction

Centrifugal microfluidic CD platforms offer many advantages over larger traditional fluidic platforms such as a reduction of the required sample/reagent volumes, portability, low fabrication cost, and full automation. In one of its simplest embodiments, a microfluidic CD platform controls fluid sequencing based on the balancing of the centrifugal force and the capillary force [1]. Examples of applications developed on the centrifugal microfluidic CD platform include enzyme linked immunosorbent assays (ELISA) [2,3], real time polymerase chain reaction (PCR) [4,5], and particle separation [6–8].

The most essential of mechanisms on a microfluidic CD is a valve that allows for fluid flow sequencing. A valve is a component that stops (normally-open valve), starts (normally-closed valve) or controls (proportional valve) fluid flow through a specialized passage or channel [1,9,10]. According to Oh et al [9], microfluidic valves fall under two main categories: passive (dependent on centrifugal forces) and active (independent of centrifugal forces) valves. Many kinds of valves fall under these two categories such as mechanical, non-mechanical, and externally actuated valves. These valves were categorized according to the mechanism of operation and/or actuation methods. For a valve to function effectively in a diagnostic process, several requirements must be met. First, it must be able to operate with relevant clinical samples and reagents of widely varying physicochemical properties typically used in diagnostic processes [1,10,11]. The valves must be unaffected by these substances to prevent the degradation of the valve before its actuation. Second, for all the steps of a traditional clinical diagnostic process to be replicated identically on a microfluidic CD platform [12] may require a multitude of valves including passive and active valves, proportional valve, normally-closed valves, and normally-open valves. Third, fluid manipulation for any diagnostic process must be tightly controlled. Failure to adhere to any of these requirements will result in rejection by the FDA and misdiagnosis of a disease or error in clinical test results, especially when biomarkers are present in very low concentrations. In general, the main criteria for a successful microvalve includes the prevention of evaporation or leakage sample, reduction of the dead volume, short time to actuation, and reduced power consumption [9].

While there are a wide variety of passive valves available, such as hydrophobic, hydrophilic, siphon, Coriolis, flap valves [1,10,12–16] etc, in most cases, these valving techniques lack a physical barrier to prevent evaporation of liquids during test storage and operation [16]. Furthermore, there are serious challenges involved in making passive valves repeatable and manufacturable. To meet the requirements for a diagnosis process, active valves are often required alone or in addition to passive valves.

University of Malaya

c. Joseph, Karunan; Ibrahim, Fatimah; Cho, Jongman, "Novel localized heating technique on centrifugal microfluidic disc with wireless temperature monitoring system," in Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE , vol., no., pp.3217-3220, 25-29 Aug. 2015. doi: 10.1109/EMBC.2015.7319077.

Novel Localized Heating Technique on Centrifugal Microfluidic Disc with Wireless Temperature Monitoring System

Karunan Joseph, Fatimah Ibrahim, *Member, IEEE* and Jongman Cho, *Member, IEEE*

Abstract—**Recent advances in the field of centrifugal microfluidic disc suggest the need for electrical interface in the disc to perform active biomedical assays. In this paper, we have demonstrated an active application powered by the energy harvested from the rotation of the centrifugal microfluidic disc. A novel integration of power harvester disc onto centrifugal microfluidic disc to perform localized heating technique is the main idea of our paper. The power harvester disc utilizing electromagnetic induction mechanism generates electrical energy from the rotation of the disc. This contributes to the heat generation by the embedded heater on the localized heating disc. The main characteristic observed in our experiment is the heating pattern in relative to the rotation of the disc. The heating pattern is monitored wirelessly with a digital temperature sensing system also embedded on the disc. Maximum temperature achieved is 82 °C at rotational speed of 2000 RPM. The technique proves to be effective for continuous heating without the need to stop the centrifugal motion of the disc.**

I. Introduction

Lab-on-a-disc or well known as the centrifugal microfluidic disc technology in recent years shows the interest of researchers in inducing the technology with biochemistry, electrochemistry and biological/medical assays[1-5]. Centrifugal microfluidic disc has a great potential in emerging as a possible solution for miniaturized and automated portable diagnostic tool in biomedical application area [6, 7]. Centrifugal microfluidic disc is often regarded as compact-disc (CD) as it portrays similar dimensions but differs in functionality aspects of the disc. Centrifugal microfluidic disc has geometrical designs of the fluidic component within the disc rather than functioning as an optical digital data storage CD[7]. The centrifugal microfluidic disc manipulates the fluidic motion confined inside the disc through geometry of channels, chambers and valving concepts. It functions when the centrifugal force is applied by spinning the disc and the spinning speed variation optimized to control the fluidic motion in the disc [8, 9]. In general, the centrifugal microfluidic discs are passive and only influenced by the applied centrifugal force. In passive mode, the discs are only capable of performing simple fluidic techniques such as mixing, valving, metering, separation and siphoning [6, 7]. The demand for more complex biomedical assays and techniques to be performed in the disc leads to the introduction of active mode [4, 7]. Active mode is a condition whereby the centrifugal microfluidic discs are enhanced with external interconnect to conduct more than fluidic automation and to perform detections, analysis, and monitoring, single-handedly. These enhancements results in a more powerful diagnostic tool. A few examples of the enhancement made are the generation of thermal energy from halogen lamps/lasers, thermoelectricity in performing Polymerase Chain Reaction(PCR) amplification, wax-valves triggering options, fluidic transfer motions, micro-balloons and pneumatic pumping application for efficient fluid handling [10-12]. Besides the thermal energy generation, electrical interface was applied to rotating discs for applications such as electrochemical glucose concentration measurements, sample enrichments by using dielectrophoresis (DEP) and also recent electrochemical velocimetry on centrifugal microfluidic disc to measure the fluid flow [3, 4, 9]. These well-developed solutions are indeed great breakthroughs in the centrifugal microfluidic technology and indirectly highlights the need for an power source to perform the desired assays on the disc[13-17]. Interfacing power supply directly to the spinning platform requires advanced modifications and it is inefficient in terms power management[18]. The inefficiency is caused by the rotational nature of the disc. It also requires the centrifugal microfluidic disc to be modified to suit the power supply interface. Besides that, the main idea of portability and efficient energy/power management will be unattainable.

In this paper, we report a novel technique of localized heating on centrifugal microfluidic disc powered by a power harvester disc. The technique is achieved by embedding the localized heating disc on the power harvester disc as shown in Fig. 1. The power harvester disc generates electrical energy from the rotation of the disc using electromagnetic induction mechanism. Generated energy is directly supplied to the heater embedded in the localized heating disc. The heat generation in relative to the rotational speed is observed. A

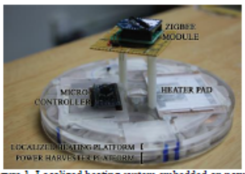

Figure 1. Localized heating system embedded on power harvester platform.

*This research is supported by Fundamental Research Grant Scheme (FRGS: FP042-2013B) and University of Malaya Research Grant (UMRG: RG009A-13AET). Fatimah Ibrahim would like to acknowledge Sultan Iskandar Johor Foundation for funding the Special Equipment Grant.

Karunan Joseph is with Centre for Innovation in Medical Engineering, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.

Fatimah Ibrahim is with Centre for Innovation in Medical Engineering, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia(phone: +603 7967 6818; fax: +603 7967 4579; e-mail: fatimah@um.edu.my).

Jongman Cho is with Department of Biomedical Engineering, Inje University, Gimhae, South Korea (e-mail: minerva@inje.ac.kr).

978-1-4244-9270-1/15/$31.00 ©2015 IEEE 3217

University of Malaya

d. Al-Faqheri, Wisam; Ibrahim, Fatimah; Thio, Tzer Hwai Gilbert; Joseph, Karunan; Mohktar, Mas S.; Madou, Marc, "Liquid density effect on burst frequency in centrifugal microfluidic platforms," in Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE , vol., no., pp.3221-3224, 25-29 Aug. 2015. doi: 10.1109/EMBC.2015.7319078.

Liquid Density Effect on Burst Frequency in Centrifugal Microfluidic Platforms*

Wisam Al-Faqheri, Fatimah Ibrahim, *Member, IEEE*, Tzer Hwai Gilbert Thio, Karunan Joseph, Mas S. Mohktar, and Marc Madou

Abstract— **Centrifugal microfluidic platforms are widely used in various advanced processes such as biomedical diagnostics, chemical analysis and drug screening. This paper investigates the effect of liquid density on the burst frequency of the centrifugal microfluidic platform. This effect is experimentally investigated and compared to theoretical values. It is found that increasing the liquid density results in lower burst frequency and it is in agreement with theoretical calculations. Moreover, in this study we proposed the use of the microfluidic CD platform as an inexpensive and simple sensor for liquid density measurements. The proposed liquid sensor requires much less liquid volume (in the range of microliters) compared to conventional density meters. This study presents fundamental work which allows for future advance studies with the aim of designing and fabricating centrifugal microfluidic platforms for more complex tasks such as blood analysis.**

I. Introduction

Over the last few decades, microfluidic-based platforms have become a focus of attention due to their capacity to address problems such as the consumption of high volumes of expensive reagents, long processing time, and expensive complex equipment used today to perform most diagnostic tests. Specifically, centrifugal microfluidic platform or as it is well known as the microfluidic CD, obviate the need for expensive external pumps and conventional mechanical valves (Madou et al., 2006). Instead, microfluidic CDs operate on the principle of the centrifugal force generated by the spinning process to move liquids toward the outer edge of the platform (pumping) and liquids are retained by capillary forces till the centrifugal force overcomes the surface tension forces (valve controlled by the burst frequency) (Madou et al., 2006; Tzer Hwai Gilbert Thio et al., 2013). Microfluidic CD can perform different processes. Microfluidic CDs can perform different processes in parallel such as calibration, metering, sample splitting, flow rate control, siphoning, decanting, etc. (Aeinehvand et al., 2013; Al-Faqheri et al., 2013; Ducr´ee et al., 2007; Madou et al., 2006; Zoval & Madou, 2007).

Recently, microfluidic CDs have been featured in a wide variety of applications. An Enzyme-Linked Immunosorbent Assay (ELISA) has been performed successfully on a LOD in a fully automated portable format; in this work Lai *et al.* (2004) performed rat Immunoglobulin type G (IgG) antigen detection on a microfluidic CD from a hybridoma cell culture. Yusoff *et al.* (2009) and Ibrahim *et al.* (2010) proposed simple designs of microfluidic CDs for Dengue fever detection; microfluidic CD were constructed by CNC machining features om a PMMA disc and sealing this machined layer with Adhesive Sealing Film (ASF). In a recent study, Al-Faqheri *et al.* (2015) proposed a fully automated ELISA on a CD utilizing novel check valves. Amasia *et al.* (2012) and Focke *et al.* (2010) proposed LOD platforms for real-time polymerase chain reaction (PCR) amplification. In Amasia's work, the use of ice-valving as a new method to prevent samples from evaporating and mixing during the PCR heating process was introduced: a computerized solenoid-actuated heat sink and thermoelectric assembly were installed under the microfluidic CD for heating and cooling. Amasia *et al.* (2012) and Focke *et al.* (2010) both reported that PCR amplification of B. anthracis/cereus was successfully completed in 57 minutes with high specificity and efficiency. Burger *et al.* (2012) proposed an array-based microfluidic CD design that can capture, distribute, and perform multiplexed assays of particles (coated beads). The detection chamber in this case is designed with V-cup barriers to trap particles using a stopped-flow sedimentation method. The authors reported nearly 100% capturing efficiency and presented a bead-based immunoassays for IgG detection. Other ideas such as micro-particle and cell counting and separation of cells and particles were successfully performed by Imaad *et al.* (2011) and Morijiri *et al.* (2010) respectively. Other researchers reported new methods for pumping liquids back towards the center of the CD overcoming the limitation of liquids moving only centrifugally toward the edge of the CD (Abi-Samra et al., 2011; Aeinehvand et al., 2013; Kong & Salin, 2011; Tzer

* This research is supported by Fundamental Research Grant Scheme (FRGS: FP042-2013B) and University of Malaya Research Grant (UMRG: RG009A-13AET). Fatimah Ibrahim would like to acknowledge Sultan Iskandar Johor Foundation for funding the Special Equipment Grant.

W. A. F. is with the Centre for Innovation in Medical Engineering, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia (wisamfakhri83@yahoo.com).

F. I. is with the Centre for Innovation in Medical Engineering, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. (phone: +603 7967 6818; fax: +603 7967 4579; e-mail: fatimah@um.edu.my)

T. H. G. T. is with the Centre for Innovation in Medical Engineering, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. He is also with the Faculty of Science, Technology, Engineering and Mathematics, INTI International University, Persiaran Perdana BBN, Putra Nilai, 71800 Nilai, Negeri Sembilan, Malaysia. (gilbert_thio@hotmail.com).

K. J. is with the Centre for Innovation in Medical Engineering, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia (karunanj@gmail.com).

M. S. M. is with the Centre for Innovation in Medical Engineering, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia (mas_dayana@um.edu.my).

M. M. is with the Centre for Innovation in Medical Engineering, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. He is also with the Department of Biomedical Engineering and Department of Mechanical and Aerospace Engineering, University of California, Irvine, Irvine, 92697, United States (mmadou@uci.edu).

978-1-4244-9270-1/15/$31.00 ©2015 IEEE 3221

University of Malaya

APPENDIX A - MICROCONTROLER PROGRAMME CODE FOR LOCALIZED HEATING SYSTEM

```
/*****************************************************
Project : Heating(PWM) & Temparature Monitoring(I2C)
Version : V 0.2
Date    : 1/25/2015
Author  : Karunan J
Company :
Comments:

TEMPSENSOR = ADT7420


Chip type               : ATmega328P
Program type            : Application
AVR Core Clock frequency: 16.000000 MHz
Memory model            : Small
External RAM size       : 0
Data Stack size         : 512
*****************************************************/

/*****************************************************/

#include <mega328p.h>
#include <stdio.h>
#include <delay.h>

#define RD_ACK      1
#define RD_NAK      0

#define ERROR       1
#define SUCCESS     0

#define MT_START_OK         0x08
#define MT_REPt_START_OK    0x10
#define MT_SLAVE_WR_ACK     0x18
#define MT_SLAVE_WR_NAK     0x20
#define MT_DATA_WR_ACK      0x28
#define MT_DATA_WR_NAK      0x30
#define MT_SLAVE_RECV_ACK   0x40
#define MT_SLAVE_RECV_NAK   0x48
#define MT_DATA_RD_ACK      0x50
#define MT_DATA_RD_NAK      0x58

#define TEMPSENSOR_ID       0xCB
#define TEMPSENSOR_ID_ADD   0x0B

#define TEMPSENSOR_TEMP_VAL_ADD   0x00

#define TEMPSENSOR_RD_ADD   0x93 // 1001 0010 (bit7-3 is constant)(bit 2-1 are set on chip for address change) (bit 0 is for READ(1) or WRITE(0))
#define TEMPSENSOR_WR_ADD   0x92 // 1001 0010 (bit 2-1 are set on chip for address change) (bit 0 is for READ(1) or WRITE(0))

#define Kp  1.0
#define Ki  0
#define Kd  0
#define dt  0.25
#define REF_temp  30.5
```

```c
typedef unsigned char uint8_t;

void Crystal_init(void);
void usart_init(void);
void timer0_init(void);
void GPIO_init(void);

void TWI_init(void);

void TEMPid_CHECK(void);
void TEMPoutput_READ(void);

//void PID_Control(void);

uint8_t TWI_start(void);
void    TWI_stop(void);
uint8_t TWI_write(uint8_t data);
uint8_t TWI_read(uint8_t* pData, uint8_t ack);

uint8_t ADT7420_ID_RD(uint8_t* pData);
uint8_t ADT7420_TEMP_RD(uint8_t* pData);


static unsigned int PWM_DUTY = 0;
static int f = 0;
//int n;

bit PID_flag;

uint8_t RData;

uint8_t temp[2];
unsigned int raw_temp;
float real_temp;

/****************************************************/

void main(void)
{
    Crystal_init();
    GPIO_init();
    timer0_init();
    usart_init();

    // Global enable interrupts
    #asm("sei")

    TWI_init();

    TEMPid_CHECK();


    while (1)
    {
        if(PID_flag)
        {
            TEMPoutput_READ();
        }
    }
}


/****************************************************/
```

University of Malaya

```
/*****************************************************/
/*****************************************************/
// TEMP SENSOR OUTPUT DATA READING
/*****************************************************/
void TEMPoutput_READ(void)
{
    if ((ADT7420_TEMP_RD(&temp[0])== SUCCESS))
        {
            raw_temp = temp[0]*256 + temp[1];
            real_temp = ((float)raw_temp / (16.0 * 8.0));  // multiply
with 1000 to avoid floating point number
            printf("Temp=%f\n", real_temp);

            //delay_ms(500);
        }
         else
        {
            printf("\nTEMP SENSOR TEMP READ Error");
            while (1);
        }
}


/*****************************************************/
/*****************************************************/
// TEMP SENSOR ID CHECK
/*****************************************************/
void TEMPid_CHECK(void)
{
    if (ADT7420_ID_RD(&RData)== SUCCESS)
        {
           printf("TEMP SENSOR ID = %02X\n\r", RData);
        }
        else
        {
           printf("TEMP SENSOR ID READ Error");
           while (1);
        }
}

/**************************************************************/
/**************************************************************/
// PWM_DUTY: Timer 0 output compare A interrupt service routine
/**************************************************************/
interrupt [TIM0_COMPA] void timer0_compa_isr(void)
{
    //static int f = 0;

    //PWM_DUTY = 255;
    OCR0B = PWM_DUTY;
    //OCR0A = PWM_FREQ;

    f++;

    if(f == 250)
    {
        PID_flag = 1;
        f = 0;
    };
}

/*****************************************************/
/*****************************************************/
```

```
 //Crystal Oscillator division factor: 1
/*****************************************************/
void Crystal_init(void)
{
    #pragma optsize-
    CLKPR=0x80;
    CLKPR=0x00;
    #ifdef _OPTIMIZE_SIZE_
    #pragma optsize+
    #endif
}

/*****************************************************/
/*****************************************************
 USART initialization
 BD: 2MBPS, Double Speed  //115200kbps
*****************************************************/
void usart_init(void)
{
    UCSR0A=0x02;
    UCSR0B=0x18;
    UCSR0C=0x06;
    UBRR0H=0x00;
    UBRR0L=0x10;
}

/*****************************************************/
/*****************************************************
 Timer0 initialization (PWM Output)
 TCCR0B (bit 0 - 1) : Clock Speed 250kHz
 TCNT0 : PWM duty Cycle control (250)
 TIMSK0: Timer/Counter 0 Interrupt(s) initialization
 OCR0A : PWM FREQUENCY setting    //250 results to 1 ms
 OCR0B : PWM DUTY CYCLE setting
*****************************************************/
void timer0_init(void)
{
    TIMSK0=0x02;

    TCCR0A=0x23;
    TCCR0B=0x0B;
    TCNT0=0x00;
    OCR0A=0xFA;     //250 results to 1 ms
    OCR0B= 0x00;
}

/*****************************************************/
/*****************************************************
 GPIO Initialization
 Port B, C, D
 PORTx : INPUT/OUTPUT Function (1= input: pullup enabled)
 DDRx  : PIN STATE  (1: input)
 PC5 & PC4 Pullup enabled, set as output mode   (tri-state)
*****************************************************/
void GPIO_init(void)
{
    PORTB=0x00;
    DDRB=0x01;

    PORTC |= 0x30;
    DDRC &= ~0x30;

    PORTD  = (1<<PORTD5)|(1<<PORTD3) ;     //|= 0x28;
    DDRD  = (1<<DDD5)|(1<<DDD3) ;      //&= ~0x28;
```

```
}

/***************************************************/
/***************************************************
 TWI Initialization (I2C Compatible)

 TWSR: Bit 0-1 Set Prescaler (0x00)
 TWBR: Bit Rate (12) :: To get 400kHz match with ADT7430
 TWCR: Bit 2 :: TWI Enable for all operation
***************************************************/
void TWI_init(void)
{
    TWSR = 0x00;
    TWBR = 0x0C;

    TWCR = (1 << TWEN);
}

/***************************************************/
/***************************************************
 TWI (I2C Compatible) - START (Returns Status Code)

 TWCR: Bit 7(TWINT) :: TWI Interupt Flag(Starts the operation of
current TWI) (1 = CLEAR, 0 = SET)
 TWCR: Bit 5(TWSTA) :: Device becomes Master, Checks Data bus
availability, Generates Start Condition
 TWCR: Bit 2(TWEN)  :: TWI Enable for all operation
 TWSR: Bit 7-3      :: Status Register
***************************************************/
uint8_t TWI_start(void)
{
    TWCR = (1 << TWINT) | (1 << TWSTA) | (1 << TWEN);

    // wait until TWINT is set.
    // TWINT set indicates START condition transmitted
    while ((TWCR & (1 << TWINT)) == 0);

    // return the status code of the transmission
    return TWSR & 0xF8;
}

/***************************************************/
/***************************************************
 TWI (I2C Compatible) - STOP

 TWCR: Bit 7(TWINT) :: TWI Interupt Flag(Starts the operation of
current TWI) (1 = CLEAR, 0 = SET)
 TWCR: Bit 4(TWSTo) :: Device becomes Master, Checks Data bus
availability, Generates Start Condition
 TWCR: Bit 2(TWEN)  :: TWI Enable for all operation
***************************************************/
void TWI_stop(void)
{
    TWCR = (1 << TWINT) | (1 << TWSTO) | (1 << TWEN);
}

/***************************************************/
/***************************************************
 TWI (I2C Compatible) - WRITE BYTE

 TWDR: Transmit Mode: Contains the next byte to be transmitted
 TWDR: Receive Mode: Contains the last byte received
 TWCR: Bit 7(TWINT) :: TWI Interupt Flag(Starts the operation of
current TWI) (1 = CLEAR, 0 = SET)
```

```
 TWCR: Bit 2(TWEN)   :: TWI Enable for all operation
 TWSR: Bit 7-3       :: Status Register
*****************************************************/
uint8_t TWI_write(uint8_t data)
{
    TWDR = data;
    TWCR = (1 << TWINT) | (1 << TWEN);

    // wait until TWINT is set.
    // TWINT set indicates current condition transmitted
    while ((TWCR & (1 << TWINT)) == 0);

    // return the status code of the transmission
    return TWSR & 0xF8;
}

/*****************************************************/
/*****************************************************
 TWI (I2C Compatible) - READ BYTE

 TWDR: Transmit Mode: Contains the next byte to be transmitted
 TWDR: Receive Mode: Contains the last byte received
 TWCR: Bit 7(TWINT) :: TWI Interupt Flag(Starts the operation of
current TWI) (1 = CLEAR, 0 = SET)
 TWCR: Bit 2(TWEN)   :: TWI Enable for all operation
 TWCR: Bit 6(TWEA)   :: TWI control of acknowledge pulse generation
 TWSR: Bit 7-3       :: Status Register
*****************************************************/
uint8_t TWI_read(uint8_t* pData, uint8_t ack)
{
    if (ack == RD_ACK)
        TWCR = (1 << TWINT) | (1 << TWEN) | (1 << TWEA);
    else
        TWCR = (1 << TWINT) | (1 << TWEN);

    // wait until TWINT is set.
    // TWINT set indicates current condition transmitted
    while ((TWCR & (1 << TWINT)) == 0);

    // read data
    *pData = TWDR;

    // return the status code of the transmission
    return TWSR & 0xF8;
}

/*****************************************************/
/*****************************************************
 TEMP SENSOR ID Read
*****************************************************/
uint8_t ADT7420_ID_RD(uint8_t* pData)
{
    // TWI START Sending
    // Check START transmission status
    if (TWI_start()!= MT_START_OK)
    {
      printf("\nSTART TX ERROR ID") ;
      return ERROR;
    }

    // TWI TEMP SENSOR WRITE Address Sending
    // Check TEMP SENSOR WRITE Address transmission status
    if (TWI_write(TEMPSENSOR_WR_ADD) != MT_SLAVE_WR_ACK)
    {
```

```
    printf("\nMT-SL ADD WR ERROR");
    return ERROR;
  }

  // TWI TEMP SENSOR ID Address Sending
  // Check TEMP SENSOR ID Address transmission status
  if (TWI_write(TEMPSENSOR_ID_ADD) != MT_DATA_WR_ACK)
  {
    printf("\nMASTER-SLAVE ID WR ERROR");
    return ERROR;
  }

  // TWI REPEAT START Sending
  // Check START transmission status
  if (TWI_start() != MT_REPt_START_OK)
  {
    printf("\nRepeat START ERROR");
    return ERROR;
  }

  // TWI TEMP SENSOR READ Address Sending
  // Check TEMP SENSOR READ Address transmission status
  if (TWI_write(TEMPSENSOR_RD_ADD) != MT_SLAVE_RECV_ACK)
  {
    printf("\nMASTER-SLAVE ADD RD ERR");
    return ERROR;
  }

  // TWI TEMP SENSOR ID READ Sending
  // Check TEMP SENSOR READ Address transmission status
  if (TWI_read(pData, RD_NAK) != MT_DATA_RD_NAK)
  {
    printf("\nMASTER-SLAVE ID RD ERR");
    return ERROR;
  }

  TWI_stop();

  return SUCCESS;
  }

/***************************************************/
/***************************************************
 TEMP SENSOR TEMPERATURE Read
***************************************************/
uint8_t ADT7420_TEMP_RD(uint8_t* pData)
{
  // TWI START Sending
  // Check START transmission status
  if (TWI_start()!= MT_START_OK)
  {
    printf("\nSTART TX ERROR RD = %02X", TWI_start()) ;
    return ERROR;
  }

  // TWI TEMP SENSOR WRITE Address Sending
  // Check TEMP SENSOR WRITE Address transmission status
  if (TWI_write(TEMPSENSOR_WR_ADD) != MT_SLAVE_WR_ACK)
  {
    printf("\nMT-SL ADD WR ERROR");
    return ERROR;
  }

  // TWI TEMP SENSOR ID Address Sending
```

University of Malaya

```
    // Check TEMP SENSOR ID Address transmission status
    if (TWI_write(TEMPSENSOR_TEMP_VAL_ADD) != MT_DATA_WR_ACK)
    {
      printf("\nMT-SL TEMP ADD WR ERROR");
      return ERROR;
    }

    // TWI REPEAT START Sending
    // Check START transmission status
    if (TWI_start() != MT_REPt_START_OK)
    {
      printf("\nRepeat START ERROR");
      return ERROR;
    }

    // TWI TEMP SENSOR READ Address Sending
    // Check TEMP SENSOR READ Address transmission status
    if (TWI_write(TEMPSENSOR_RD_ADD) != MT_SLAVE_RECV_ACK)
    {
      printf("\nMT-SL ADD RD ERROR");
      return ERROR;
    }

    // TWI TEMP SENSOR ID READ Sending
    // Check TEMP SENSOR READ Address transmission status
    if (TWI_read(pData, RD_ACK) != MT_DATA_RD_ACK)
    {
      printf("\nMT-SL TEMP DATA RD ERROR #1");
      return ERROR;
    }

    if (TWI_read(pData+1, RD_NAK) != MT_DATA_RD_NAK)
    {
      printf("\nMT-SL TEMP DATA RD ERROR #2");
      return ERROR;
    }

    TWI_stop();

    return SUCCESS;
}
```

University of Malaya