DEVELOPMENT OF DRUG DELIVERY DEVICE USING PHASE CHANGE MATERIAL

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Electrical and Electronics Engineering

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August 2016

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DEVELOPMENT OF DRUG DELIVERY DEVICE USING PHASE CHANGE MATERIAL"** was prepared by **JOSEPH YU CHUI SIM** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Electrical and Electronics Engineering at Universiti Tunku Abdul Rahman.

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Signature : ______________________________

Supervisor : ______________________________

Date : ______________________________

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ABSTRACT

This project aims to develop a drug delivery device by using phase change material. In drug delivery systems, there is plenty of research which use micro-actuation to deliver drug. Moreover, the micro-actuation principle such as shape memory alloy, electromagnetic and piezoelectric, involve complex fabrication and expensive in term of price. These types of micropump also have drawbacks of low volumetric expansion. With the advantages of large volumetric expansion and economical price, phase change material was used in this project. In this project, Polydimethylsiloxane (PDMS) was used as the structure of the drug reservoir. Copper etching technique was used to etch heater on a printed circuit board (PCB). The proposed device successfully show a proof of concept in drug delivery.

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CHAPTER 1

INTRODUCTION

1.1 Background

In 21st Century, Micro-Electro Mechanical Systems (MEMS) technology is one of the most promising technologies. MEMS technology is a process technology which creates micro-size integrated devices. MEMS can be recognized as systems which consist of both electrical and mechanical components. In MEMS, the devices or components used are all in micro-scale which the dimension of the components are just a few micrometre cube or millimetre cube. These tiny devices or systems still have the ability to sense, control and actuate. MEMS had started a great revolution in both industrial and consumer products. Most of MEMS uses the combination of silicon-based microelectronics with micro-machining technology. Nowadays, MEMS became a part of everyday life and can be found in digital micro-mirror devices (DMD) for HDTVs or projectors, ink-jet heads in printers, various sensors in automobiles and others applications (Lehto, 2007). By choosing components that are made by micromachining, processing in batches can lower the production costs. As we all know, reduction of cost is one of the major driving forces for technological development.

In the past decade, MEMS technology has been applied to drug delivery devices. The most common methods of drug delivery include oral, injection, inhalation and etc. For example, localized drug delivery provides the advantages of controllable dosage of drug at targeted area. This kind of drug delivery can maintain the effectiveness of the concentration of drug at local decease site. Besides that, localized drug delivery also reduces the chances of harmful side effects and systemic toxicity. MEMS-based drug delivery devices that are enables complex dosing schedules and maintain stability of drug that contained in reservoirs for certain periods.

Recently, researches of micro-actuator have been proposed (Niezrecki et al., 2001). An actuator is a device that converts an electrical signal into mechanical action. The actuator can create a force to control either itself or other devices or even the surrounding environment in order to perform certain functions. The actuator can be in the form of piezoelectric, electromagnetic, electrostatic and etc. In this project, Phase Change Material (PCM) had been used which this material can provide one of the highest energy density micro-actuation methods.

1.2 Problem Statement

With the help of MEMS technology, drug delivery had entered a new era of development. The principle of micropumps are one of the key elements in drug delivery especially for the controlled propulsion of fluids. Several micropumps concepts and prototypes are developed and studied by researchers. These micropumps can pump out the drug from the device which is in micro-sized. However, the fabrication method proposed is difficult in fabrication (Lehto, 2007) and the cost is very expensive. Thus, economic pricing with advanced technology is essential to ensure the prototype able to gain strong market demand. Moreover, many researchers has done developments of micropumps by using piezo-electric (Niezrecki et al., 2001), electrochemical (Li et al., 2008) and electromagnetic (Zachkani et al., 2015) approaches. These approaches are using complicated fabrication technology and this may lead to expensive cost. Thus, this project aims to develop a new economical drug delivery approach by using phase change material.

1.3 Aim and Objectives

The aim of this project is to propose drug delivery device by using phase change material. The device is using principle of micropumps to deliver the drug. This device will provide a localized drug delivery which is capable of providing controlled drug delivery.

The objectives of this project are shown as following:

- To design a drug delivery device using phase change material approaches.
- To characterize the drug delivery device proposed.

1.4 Scope

The structure of this thesis will be as followed:

- Chapter 2, literature review on drug delivery, phase change material, paraffin wax and its actuator.
- Chapter 3, methodology on the fabrication of the structure and heater.
- Chapter 4, results obtained from experimental procedure and discussion on the results.
- Chapter 5, conclusion about the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Drug Delivery Device

Drug delivery can be referred as approaches, technologies and systems to transport a drug or pharmaceutical compound within human body. Drug delivery may involve some scientific site-targeting within human body. In any cases, drug delivery is typically concern about the quantity and duration of drug presence. Drug delivery technologies include absorption, drug release, distribution, elimination and etc. These technology is to improve the products safety and efficiency. Targeted delivery, which nowadays scientist put a lot of efforts on it, is the development of drug delivery where the drug is only active in the target area of the body. An overview of the main routes of drug administration is represented in Figure 2.1. This overview is showing the drug delivery routes by using microsystem technology approaches.

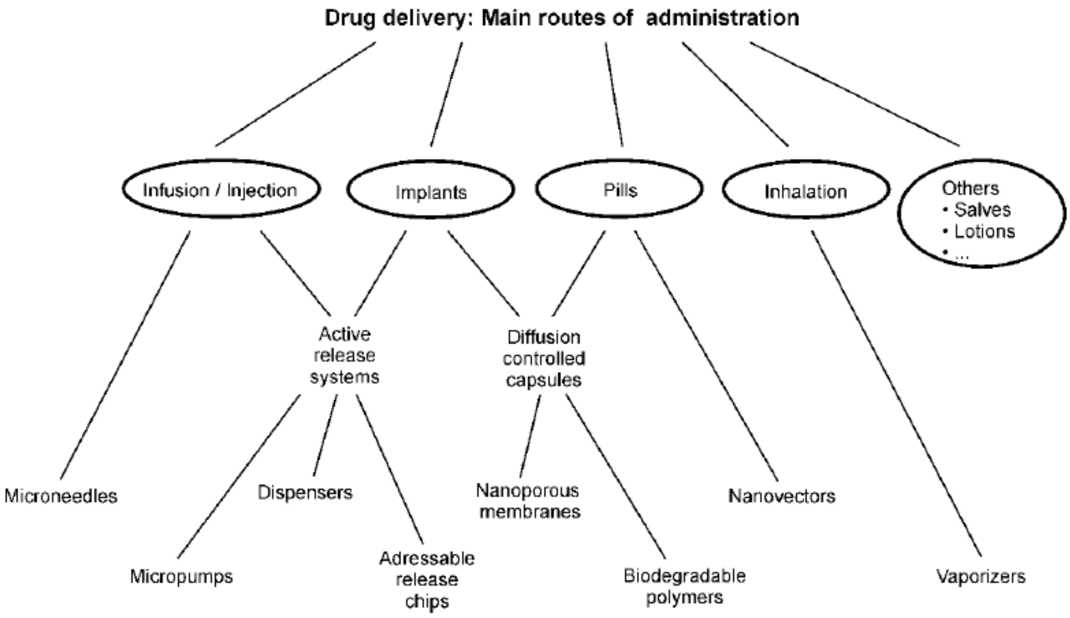

Figure 2.1: Overview of routes of drug administration (Geipel, 2008)

By using MEMS, drug delivery had improved in the field of implantable solutions, painless injections and automated infusion (LaVan, McGuire and Langer, 2003). For example, silicon-based microneedle fabricated by using deep reactive ion etching technology (Nuxoll and Siegel, 2009). The saw tooth structures shown in Figure 2.2 are just 150-300 μm long and nearly 250 μm wide. They had been used for clinical trials for insulin delivery, administration of influenza vaccine and also local anesthesia (Van Damme et al., 2009).

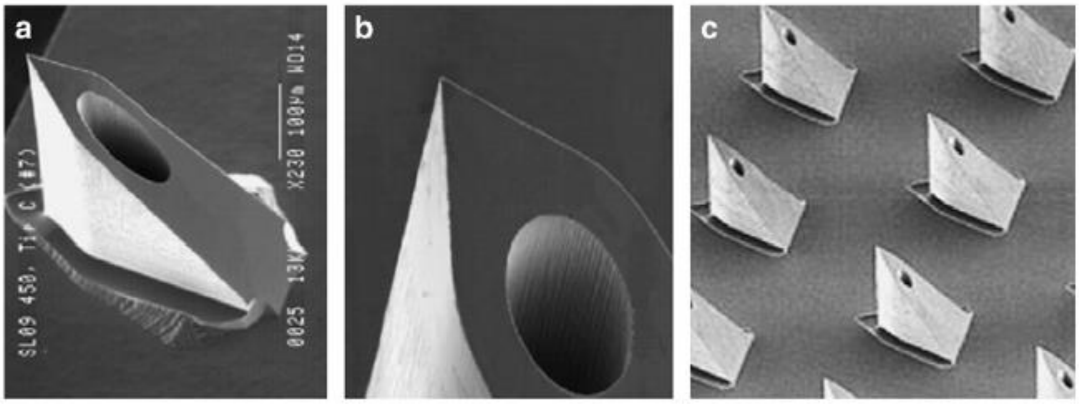

Figure 2.2: Saw tooth structures of microneedle (Gardeniers et al., 2008)

For implantable delivery system, it can be divided into two categories (Staples et al., 2006). Firstly is passive system, where drug release cannot be controlled after implantation and is pre-determined by the fabrication methods, materials, or drug formulation. Passive system utilize concentration gradients, osmotic potential or diffusion as their driving force. Another is active system, where drug release is controlled after implantation using electrical, mechanical, laser or magnetic. Active system requires actuation methods such as mechanical pumping and electrolysis.

For active delivery system mentioned above, micropumps are considered as a very significant component. A micropump usually consists of an actuator, valves and a drug reservoir. These micropumps will control the delivery of small amount of a drug accurately. Normally an actuation will be used in micropumps such as piezoelectric actuation, magnetic actuation, electrolysis or resistive heating. An example of micropumps application shown in Figure 2.3.

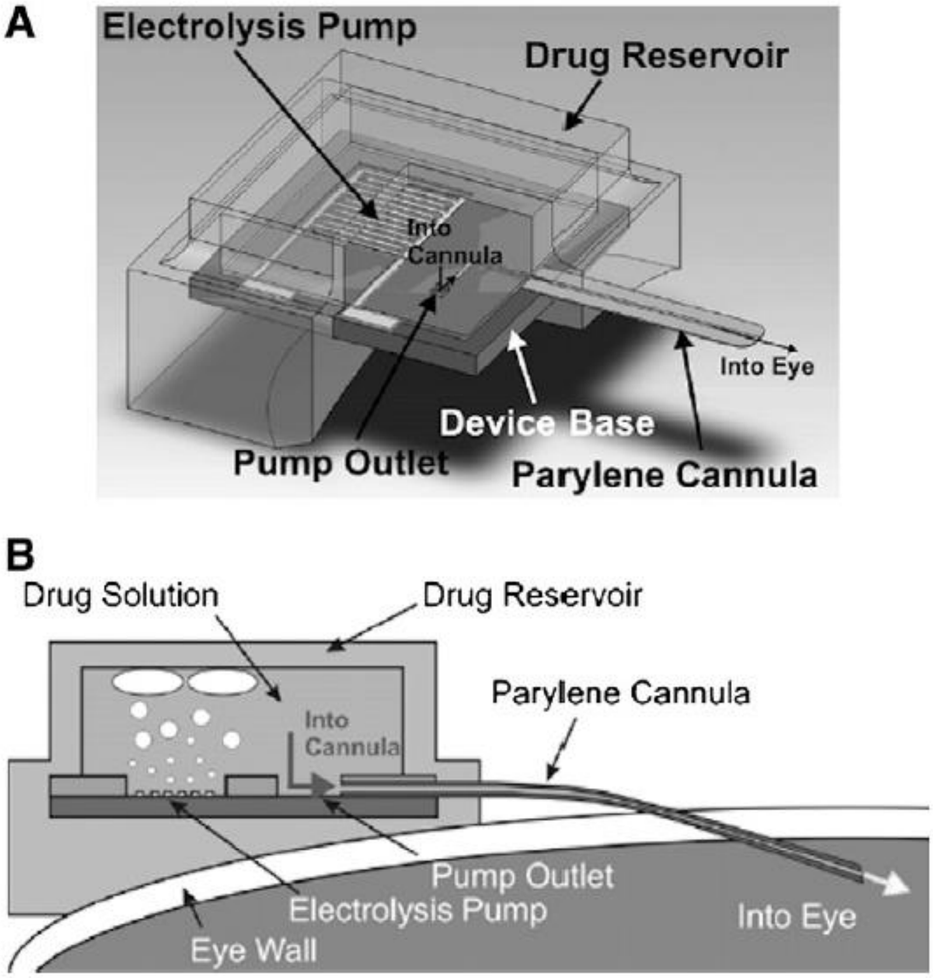

Figure 2.3: Active delivery pump for ophthalmic use (Li et al., 2008)

The device in Figure 2.3 contains a one-way valve made of parylene and a refillable drug reservoir. This device is surgically implanted with a flexible parylene cannula beneath the conjunctiva and inserted through the eye wall. When a dose is required, current will flow through two electrodes located on the silicon in contact with the drug solution and generate gas by electrolysis. The gas generated will increases the pressure and causing the flexible membrane of the drug reservoir to deflect and push the drug into the eye through the cannula (Li et al., 2008).

Another example of micropump application is an ocular drug delivery implant actuated by magnetic field as shown in Figure 2.4. This is a research done by the University of British Columbia for the treatment of diabetic retinopathy (Pirmoradi et al., 2011). The device is designed to be surgically implanted behind the eye. This prototype implant consisted of a reservoir with dimensions of 6 mm × 550 μm which contains docetaxel and sealed with an elastic magnetic polydimethylsiloxane (PDMS) membrane with dimensions of 6 mm × 40 μm. When magnetic field is applied, the membrane deforms, creating a pressure to expulse the drug from the implant.

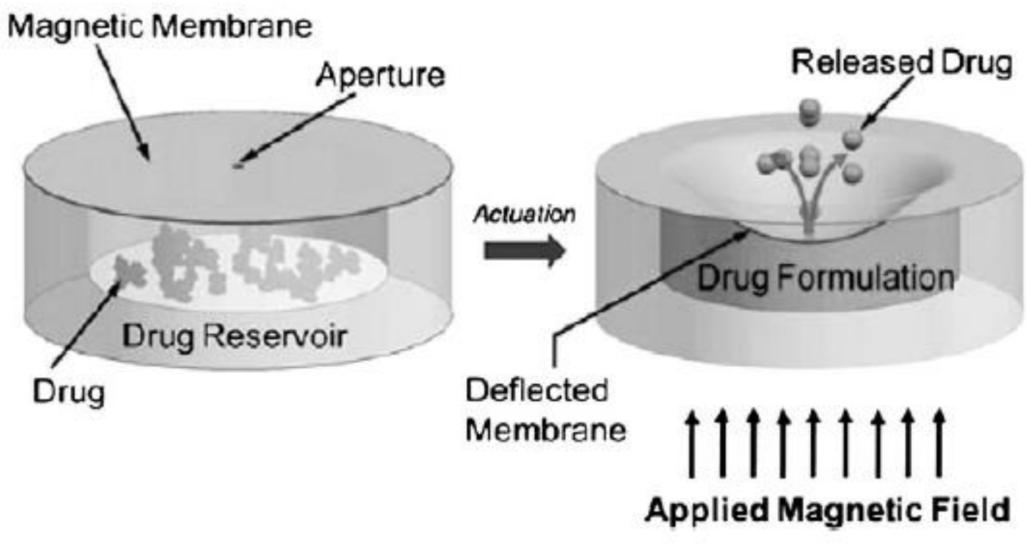

Figure 2.4: Ocular drug delivery implant actuated by magnetic field (Li et al., 2008)

From the examples mentioned above, it is clearly observed that for micropump-based drug delivery device, it usually consists of a drug reservoir and also channels or valves to allow the drug to be expulsed out of the reservoir.

2.2 Phase Change Material

Phase Change Materials (PCM) are ideal products for thermal management solutions. PCM are materials that absorb and release energy when changing from one phase to other. When PCM freeze, large amount of energy which defined as latent heat will be released at constant temperature. On the other hand, when PCM melt, the same amount of energy will be absorbed as the phase is changing from solid to liquid. In other words, heat is absorbed when the material changes from solid to liquid and released when the material changes from liquid to solid. Figure 2.5 below explains how PCM change from phase to phase. When temperature rises, PCM absorb heat and melt. When temperature decreases, PCM release heat and return to solid phase.

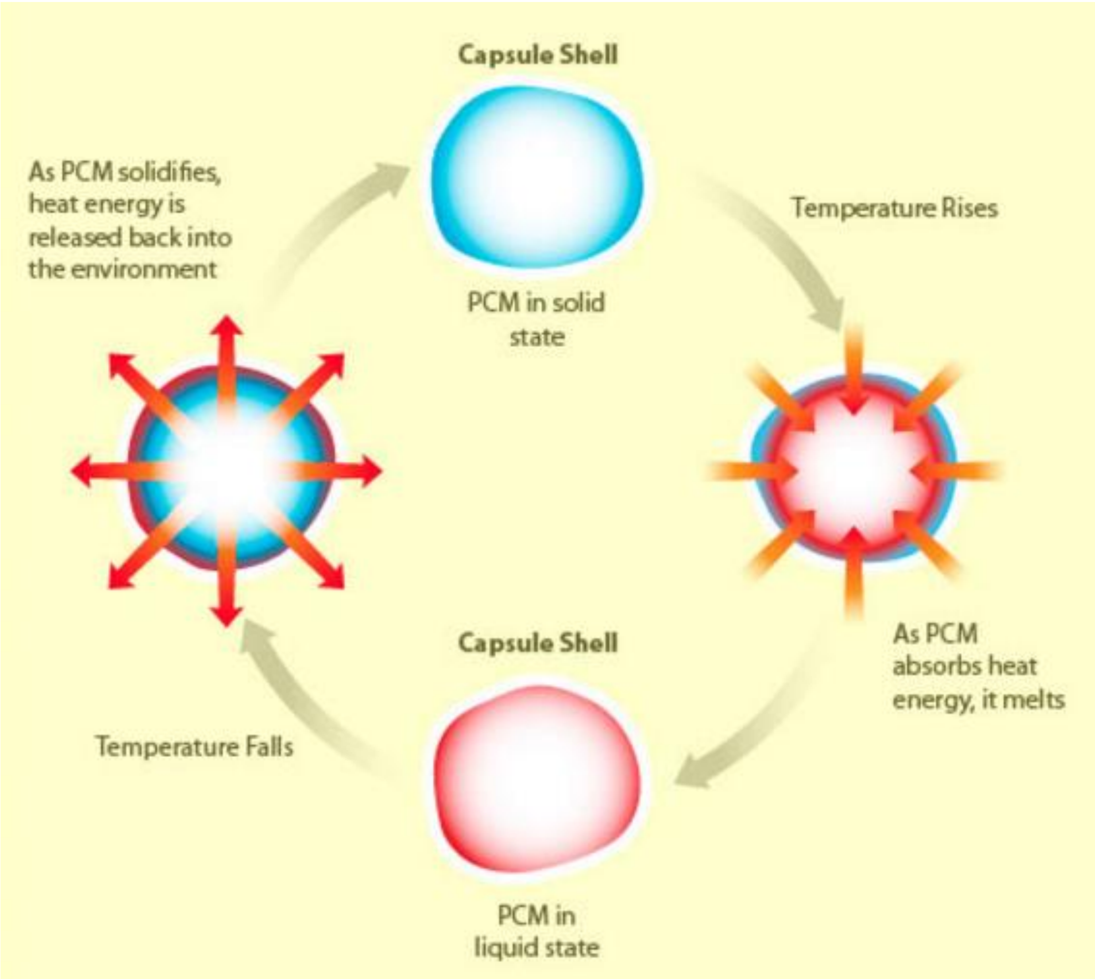

Figure 2.5: Phase Change Material oscillate between solid and liquid phases depending on temperature (Ticsay, 2012)

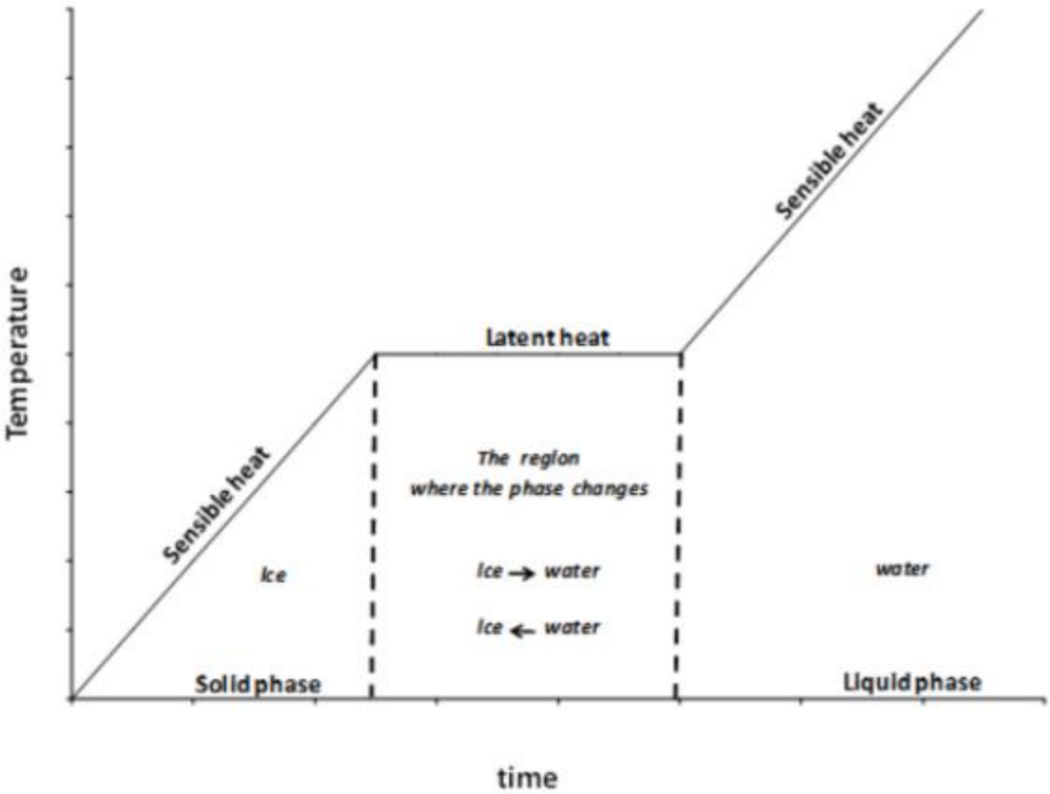

Figure 2.6: Temperature profile of Phase Change Material (Kizilel, 2007)

From Figure 2.6, when PCM change from solid phase to liquid phase, at certain point PCM will remain at constant temperature which this is known as latent heat. There is solid-liquid mixture occur when the PCM heat up to that particular temperature. And this latent heat will last for a period of time before changing into liquid phase. From the temperature profile of PCM, it can be concluded that PCM efficiently store heat in the form of latent heat. Different types of PCM will have different latent heat temperature but the temperature profile will be almost the same among PCM.

PCM can be divided into four categories (Pure Temp, 2016). First category is water-based ice and gel packs. These low-cost devices keep materials cold around 0 °C. They have the advantages of environmentally friendly, nontoxic, non-flammable and easy to use. Second category is salt hydrates which consist of inorganic salts and water. Their melting point temperatures are range between 15 °C to 18 °C. They have the advantages of low costs, high latent heat storage capacity, high thermal conductivity and inflammability. Third category is paraffin. Paraffin are derived from petroleum and is resembling wax in consistency at room temperature.

Their melting point are between -8 °C and 40 °C. They are good thermal storage capacity. They can be freezed without supercooling. They also have the characteristic of non-corrosive and compatible with most encapsulation materials. The forth category is vegetable-based or bio-based PCM. They are organic compound derived from animal fat and plant oils. Their melting point range between -40 °C and 151 °C. They are commonly derived from fatty acid. Their efficiency usually is higher than salt hydrates and paraffin (Pure Temp, 2016).

2.3 Paraffin Wax

Paraffin wax is a white or colourless soft solid derivable from petroleum. Paraffin wax is a long chain polymer which consist of the mixture of saturated alkanes or hydrocarbons, with the general formula C_nH_{2n+2}. Alkanes only consist of hydrogen and carbon atoms as shown in Figure 2.7 and no double bonds.

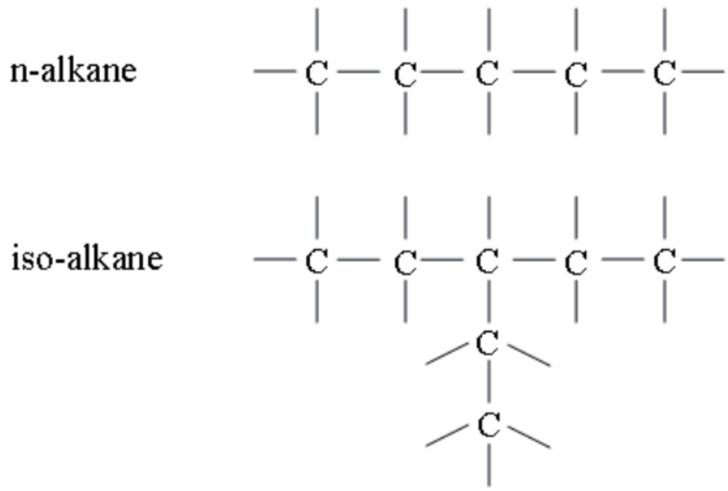

Figure 2.7: An illustration of alkanes (Lehto, 2007)

Paraffin wax is commonly used in products such as skin lotion, protective surfaces for food and window openers in green houses. Paraffin waxes change their volume at phase transitions. They are normally solid at room temperature. The phase change of paraffin wax is reversible as they are PCM. Certain heat is needed for phase changing.

Paraffin wax can be defined as PCM which is highly suitable for micro-actuation because when it melts, it will create expansion in volume of approximately 10-15 % (Geipel, 2008). Different model of paraffin wax will have different melting temperature due to the variation of hydrocarbon chain length and the temperature is ranging from -100 °C to 100 °C (Klintberg et al., 2002). Generally longer polymer chains will results in higher melting temperature. But normally the model that being used in microactuation purpose will have the meilting temperature between 35 °C to 80 °C (Geipel, 2008).

If paraffin wax is contained in a sealed vessel and being heated, the paraffin wax will melt and expand in volume. This will create a hydraulic pressure inside the vessel. Since paraffin wax generates a large hydraulic pressure, this pressure will be the driving force for the micro-actuators. Moreover, paraffin is a very cheap and easy to get material because it is a leftover from the petroleum industry. However, there is a drawback of paraffin wax. It has low thermal conductivity and large heat capacity around 170 kJ/kg (Klintberg et al., 2002). This property will results in slow thermal actuation. However, paraffin wax still have the advantages of simplicity and economic fabrication and also generates high hydraulic pressure from the expansion. Thus, paraffin wax still have good reason to be chosen in this project. The paraffin wax used in this project is from Sigma-Aldrich with 44°C to 46°C melting point.

2.4 Paraffin Wax Actuators

An actuator can be described as a transformer that can convert an electrical signal into mechanical work. There are several existing micro-actuators in different techniques such as magnetic, piezoelectric, thermal expansion, phase change and electrostatic actuation. However, by comparing the hydraulic pressure among these actuation techniques, PCM has the second highest work per unit volume as shown in Figure 2.8.

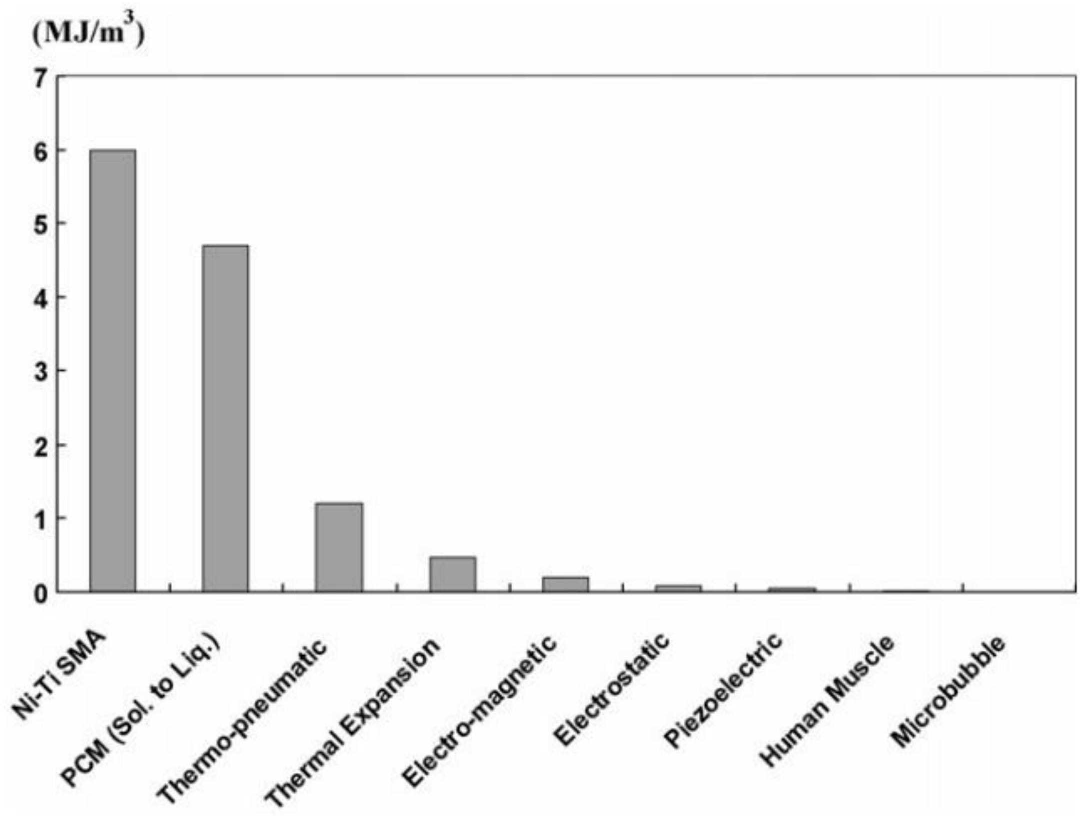

Figure 2.8: Work per unit for various microactuator types (Krulevitch et al., 1996)

Shape Memory Alloy (SMA) had been used by researchers in micro-actuation. SMA can produce both expansion and large forces in solid phase transitions. From Figure 2.8, SMA has a higher work per unit than paraffin wax. However, SMA are less suited for microfabrication. SMA are normally formed to springs and wires. It is difficult to integrating SMA at low cost in microsystem. Then, PCM which changing phase between solid and liquid state are attract researchers' interest to discover more about it. This is due to the large mechanical power produced by volumetric expansion. Unfortunately, PCM are slow to cool down due to the latent heat. But because of the simplicity and economic fabrication, paraffin wax actuators still always be chosen when discovering new technology for actuator.

The applications of paraffin wax actuator had been developed by J.S. Lee and S. Lucyszyn in 2006 (Lee and Lucyszyn, 2006). Figure 2.9 to Figure 2.12 show how paraffin wax actuator being implemented and modified by researchers.

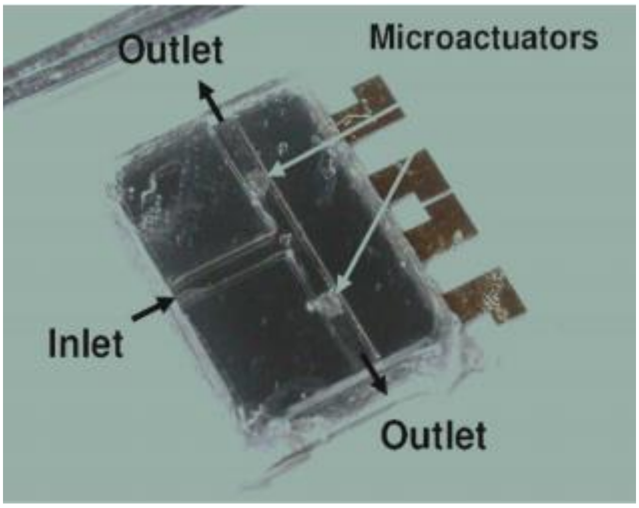

Figure 2.9: Microfluidic Valve (Lee and Lucyszyn, 2006)

From Figure 2.9 microvalve consists of 2 parrafin wax actuators at two opposited outlet channels. When microactuator operates at one of the outlet channel, let say the left outlet channel, then the deionized water will flow only through the right outlet channel. When the paraffin wax is being heat up and expand or in other words, when the parrafin wax actuator is being actuated, the channel will be blocked. And when the paraffin wax is cooling down to solid stage, the channel will be reopen to allow the deionized water to flow through it. Figure 2.10 shows the results of microvalve.

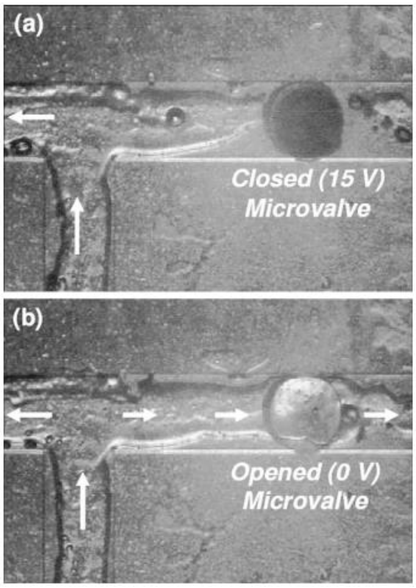

Figure 2.10: Closed Channel and opened Channel for microvalve (Lee and Lucyszyn, 2006)

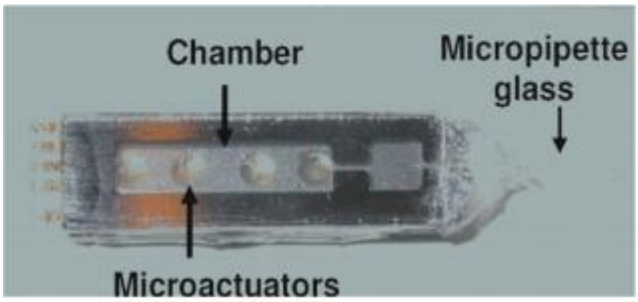

Figure 2.11: Micropipette (Lee and Lucyszyn, 2006)

From Figure 2.11, there are 4 paraffin wax actuator inside the chamber. When the power is supplied to the heater and activate the actuator, the deionized water will be expulsed out. When paraffin wax cool and return to its original position, there is a suction process occur. The maximum amount of deionized water expulsed was 6.74 µl when all the 4 microactuator was actuated (Lee and Lucyszyn, 2006). Figure 2.12 show the results of micropipette.

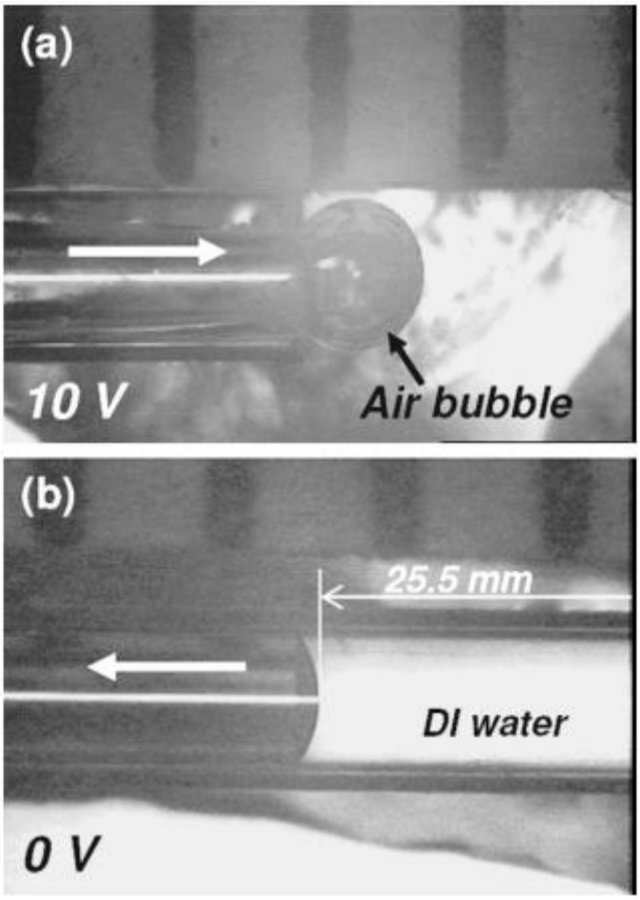

Figure 2.12: Expulsion and suction for micropipette (Lee and Lucyszyn, 2006)

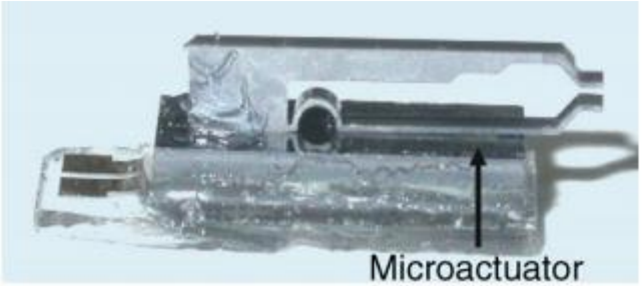

Figure 2.13: Microgripper type A (Lee and Lucyszyn, 2006)

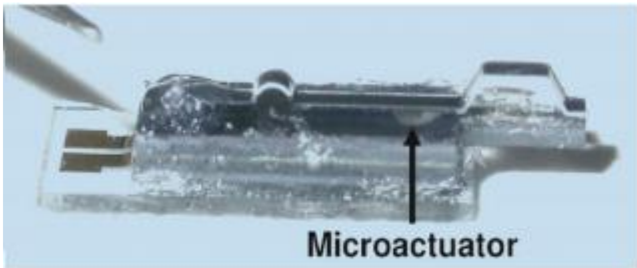

Figure 2.14: Microgripper type B (Lee and Lucyszyn, 2006)

For Figure 2.13, the microgripper type A is always opened until the microactuator actuated, then it will be in gripped position. For Figure 2.14, the microgripper is always in gripped condition. But when the microactuator actuated, it will be at opened position.

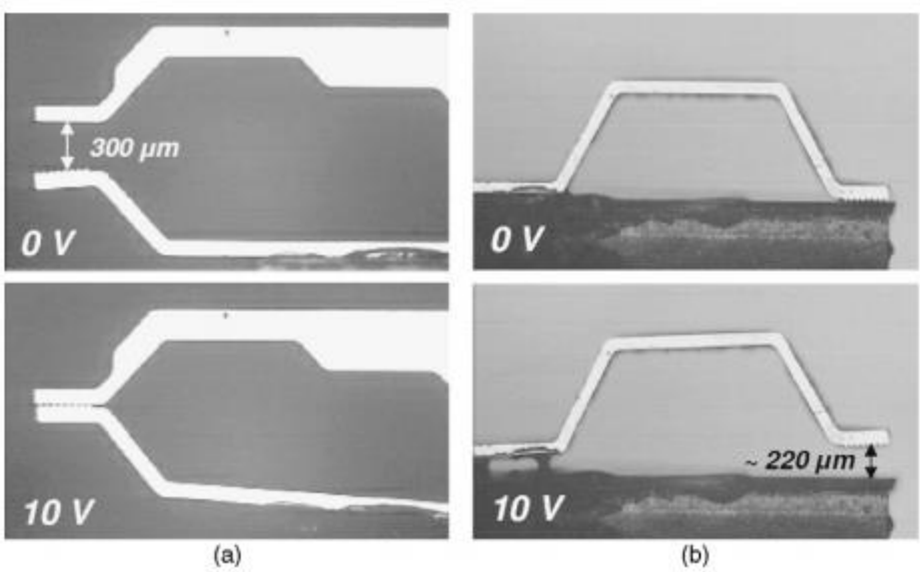

Figure 2.15: Results of microgripper (Lee and Lucyszyn, 2006)

CHAPTER 3

METHODOLOGY

3.1 Device Design

The drug delivery device has a dimension of 30 × 15 × 2 mm^3 which is the combination of 30 × 15 × 1 mm^3 PDMS structure and 30 × 15 × 1 mm^3 heater with PCB structure. The dimension is quite large in size and this is due to the technology used, which is using paper mould fabrication that shown in Chapter 3.2. The top view and side view of designed PDMS structure is shown in Figure 3.1 and Figure 3.2 respectively. The dimension of the heater is shown in Figure 3.3.

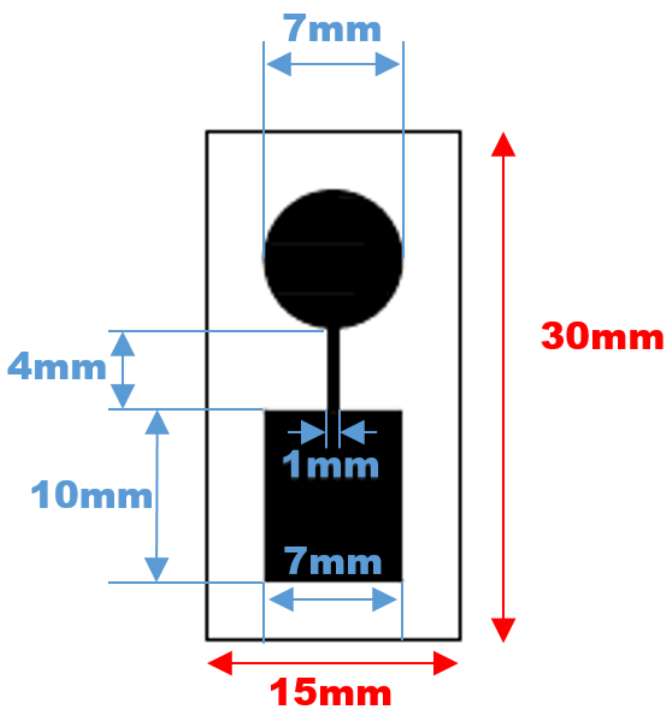

Figure 3.1: Top View and dimensions of PDMS structure.

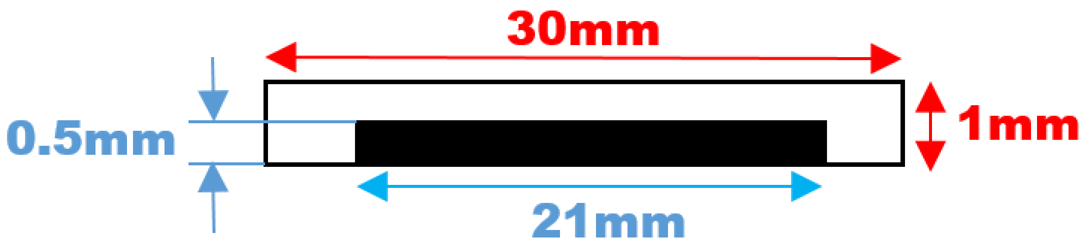

Figure 3.2: Side View and dimensions of PDMS structure.

As shown in Figure 3.2, the shaded part is where the paraffin wax and drug reservoir located. The shaded part can be divided into 3 parts. For the top part, which is the round-shaped part, it is a circle with diameter of 7 mm and thickness of 0.5 mm. This part is the drug reservoir which drug will be inserted later. For the middle part, there is a thin channel connecting the round part and rectangular part. The dimension of the thin channel or the middle part is 4 mm x 1 mm x 0.5 mm. The bottom part, which is the rectangular part is where the paraffin wax will be inserted in. The dimension of this part is 10 mm x 7 mm x 0.5 mm. The paraffin wax in solid form will fill up this portion before combine the PDMS structure with the heater. The heater design is shown in Figure 3.3.

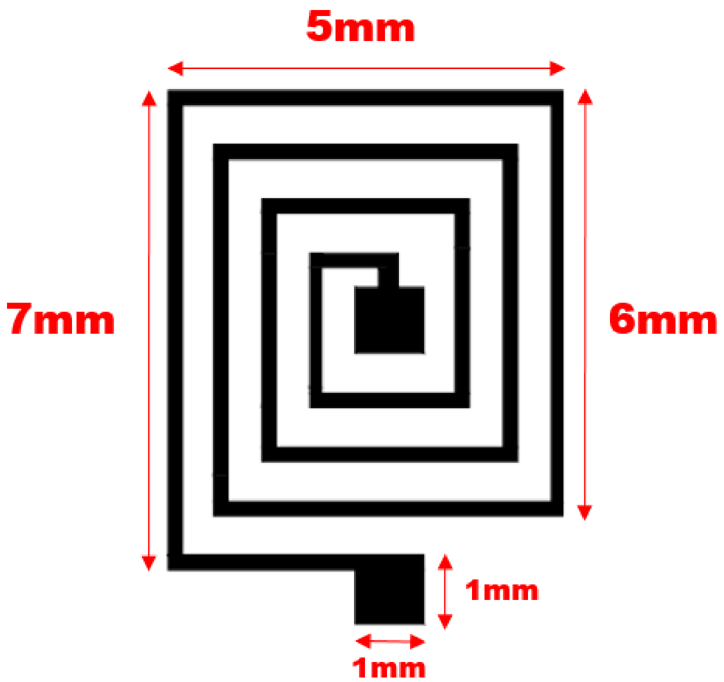

Figure 3.3: Top View and dimensions of heater structure.

The heater consists of two square with 1 mm x 1 mm dimension and also a spiral path that joined the two square. The width of the spiral path is 0.2 mm. This heater is then directly attached to the rectangular part of PDMS structure.

3.2 Fabrication

The fabrication of PDMS was done using paper mould and a petri dish as shown in Figure 3.4. The pattern of the PDMS structure was drawn by using AutoCAD. The design then was printed out on a paper with 0.5 mm thickness. After that the paper will be cut according to the shape that had been designed which is the shaded part in Figure 3.1. The paper mould was then stick to the petri dish by using double-sized PDMS thin film tape as shown in Figure 3.4.

Figure 3.4: Fabrication of PDMS structure using paper mould and petri dish.

After that, the liquid PDMS was mixed with curing agent with the ratio of 10:1. The weight balancer shown in was used to measure the weight of the PDMS and also the curing agent. The PDMS was then stirred and poured into the mould and left overnight. Next is the fabrication of heater. The design of the heater is firstly printed on a piece of tracing paper. The tracing paper with the heater design will then cut off and attached with the PCB board with photoresist on it. After that, the PCB board attached by the tracing paper will put inside the UV exposer unit for about 10 seconds. Next, PCB board was put into a container filled with sodium hydroxide and was being rinsed.

After the unwanted portion had been removed, the PCB board was taken out and put into a machine called Mega Tri-Tank to finish up the copper etching. This last step takes about one hour to finish up. Finally the heater was successfully fabricated on the PCB board as shown in Figure 3.5.

Figure 3.5: Heater on PCB board.

The rectangular cube of paraffin wax was obtained by fabricating a mould using PDMS. After that, the solid paraffin wax was added into the PDMS mould and it was put on a hot plate to melt the paraffin wax. Then, the hot plate will be switch off after the melted paraffin fully filled the mould. The paraffin wax will return to its solid stage after cooling down. Two holes were being drilled which is at the two square portion of the heater. The drill bit size of 4 mm to 5 mm was used to drill the holes.

After the PDMS was cured, the PDMS will be removed from the mould by applying some isopropanol on it at the same time. The PDMS structure is then cleaned by some isopropanol. The double-sized thin film PDMS tape was cut according to the shape shaded in Figure 3.1. After that, the paraffin wax that was moulded and solidified will be inserted into the rectangular part of the device. Then, a hole with 2 mm radius was punched at the drug reservoir side by using a belt puncher. Next, the PDMS was bonded to the heater by the double-sized thin film PDMS tape.

3.3 Characterization

In this project, the characterization that had been done is the heater characterization. For heater, thermocouple and software named BenchLink shown in Figure 3.6 and Figure 3.7 was being used. The BenchLink software can export out the temperature reading into Microsoft Excel format. The temperature will be varied with the current starting at 0.5 A to 2.0 A. All the data and analysis are recorded and tabulated in Chapter 4 and Appendix A.

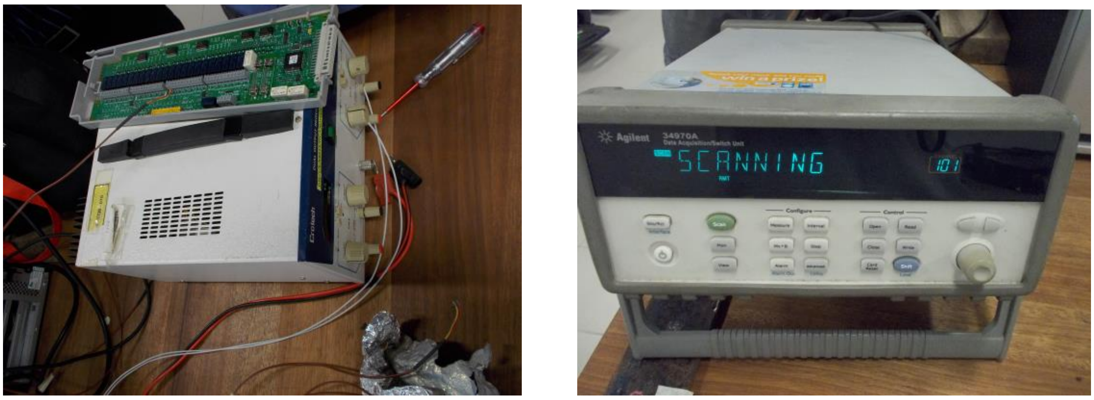

Figure 3.6: Thermocouple.

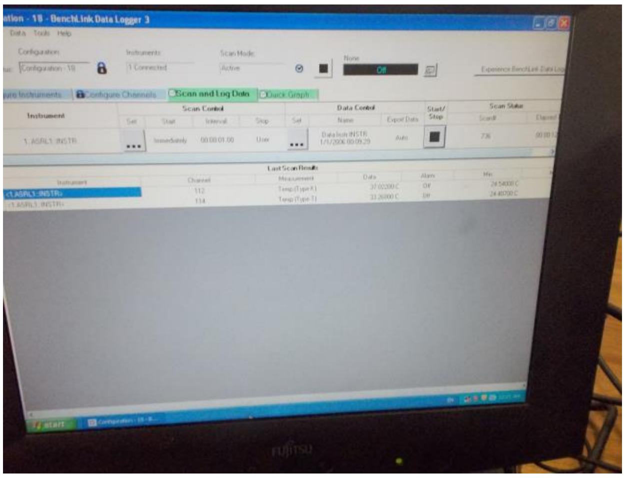

Figure 3.7: Interface of BenchLink software.

Next, the device characterization that planned to be carried out are the volume of drug delivered and time taken for the device to expulse the drug. The volume of the drug expulsed can be measured by set up the apparatus as shown in Figure 3.8.

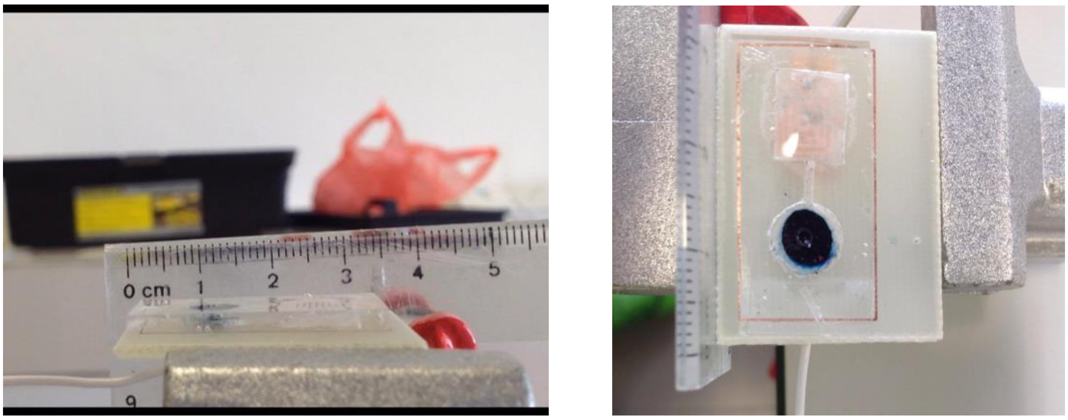

Figure 3.8: Apparatus set up to measure the volume of drug expulsed out.

The volume of drug expulsed out will be deflected into a hemispherical when it came out from the hole. The height of the hemisphere defines the height of the liquid. The volume of the drug will be calculated from the volume of the hemisphere. The expanded hemisphere was considered as a dome as shown in Figure 3.9.

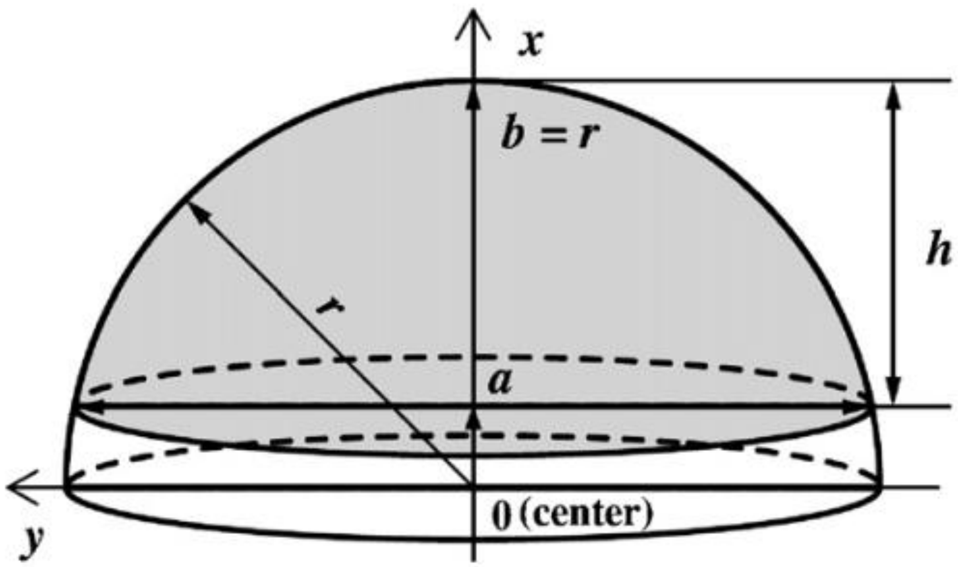

Figure 3.9: Dimensions of an actuated PDMS diaphragm.

With the given dimensions, the volume of the dome is calculated using the formula:

$$V_{dome} = \pi \int_a^b (r^2 - x^2) dx \tag{3.1}$$

where

V_{dome} = Volume of the dome, mm^3

r = spherical radius from the given bottom diameter, mm

a, b = integral on x-axis

Since the dome is part of hemisphere on x-y axis, the limits of the integral a and b are shown as points on the x-axis. Using equation (3.1), the volume of the dome is calculated. The volume of the solid paraffin wax and the container dimensions are also obtained.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Heater

The characterization of heater had been done using a thermocouple and the BenchLink software. The measurement of temperature was done at current rating from 0.5 A to 2.0 The temperature is recorded every second. The total time of recording is around 1 minutes due to the rising temperature of the heater. The temperature of the heater will rise slowly from room temperature when the current was applied to the heater. Within one minute, the temperature of the heater will rise to a stable temperature. The thermocouple has two measuring tips. One is with an insulator cover but another is without an insulator couple. The thermocouple without insulator cover will have higher temperature reading compared to the thermocouple with insulator. Thus, the average temperature reading of each tips of thermocouple needed to be calculated and tabulated in a table. Appendix A indicates the reading from BenchLink software and also graphs of the temperature calibration of the heater.

The summary of the temperature profile of the heater is then tabulated into Table 4.1. A graph is plotted to show the summary of the temperature profile of the heater as shown in Figure 4.1.

Current (A)	Temperature (°C)		
	Thermocouple Without Insulator	Thermocouple With Insulator	Average
0.5	28.93703	28.15825	28.547640
0.6	28.92645	28.53268	28.729565
0.7	30.33898	27.93919	29.139085

0.8	31.08923	29.02377	30.056500
0.9	33.00573	29.91866	31.462195
1.0	33.38944	30.30086	31.845150
1.1	36.89316	35.31340	36.103280
1.2	39.68984	35.89765	37.793745
1.3	44.93352	36.47705	40.705285
1.4	50.32087	41.27352	45.797195
1.5	50.59915	42.13878	46.368965
1.6	54.90248	44.45530	49.678890
1.7	59.02351	53.29914	56.161325
1.8	61.09393	47.47950	54.286715
1.9	70.57438	50.64763	60.611005
2.0	76.13398	58.52296	67.328470

Table 4.1: Summary of the temperature profile of the heater

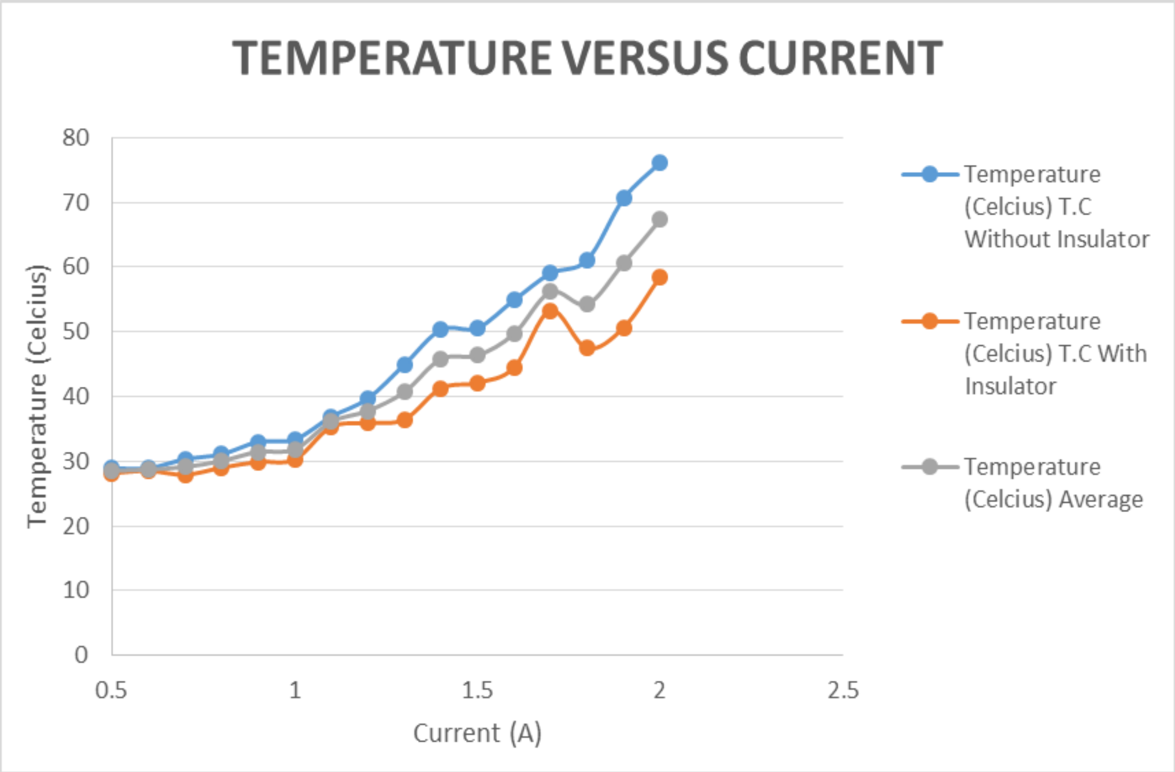

Figure 4.1: Summary of the temperature profile of the heater.

Besides that, the power that required to achieve the temperature also being calculated and tabulated based on the summary of the temperature profile. The resistance of the heater measured is 0.2 Ω. By using the power formula:

$$Power = I^2 R \tag{4.1}$$

where

I = Current supplied, A

R = Resistance of the heater, Ω

The results are tabulated in Table 4.2 and a graph is plotted as shown in Figure 4.2.

Power (W)	Temperature (°C)		
	Thermocouple Without Insulator	Thermocouple With Insulator	Average
0.050	28.93703	28.15825	28.547640
0.072	28.92645	28.53268	28.729565
0.098	30.33898	27.93919	29.139085
0.128	31.08923	29.02377	30.056500
0.162	33.00573	29.91866	31.462195
0.200	33.38944	30.30086	31.845150
0.242	36.89316	35.31340	36.103280
0.288	39.68984	35.89765	37.793745
0.338	44.93352	36.47705	40.705285
0.392	50.32087	41.27352	45.797195
0.450	50.59915	42.13878	46.368965
0.512	54.90248	44.45530	49.678890
0.578	59.02351	53.29914	56.161325
0.648	61.09393	47.47950	54.286715
0.722	70.57438	50.64763	60.611005
0.800	76.13398	58.52296	67.328470

Table 4.2: Temperature profile of the heater varied with power.

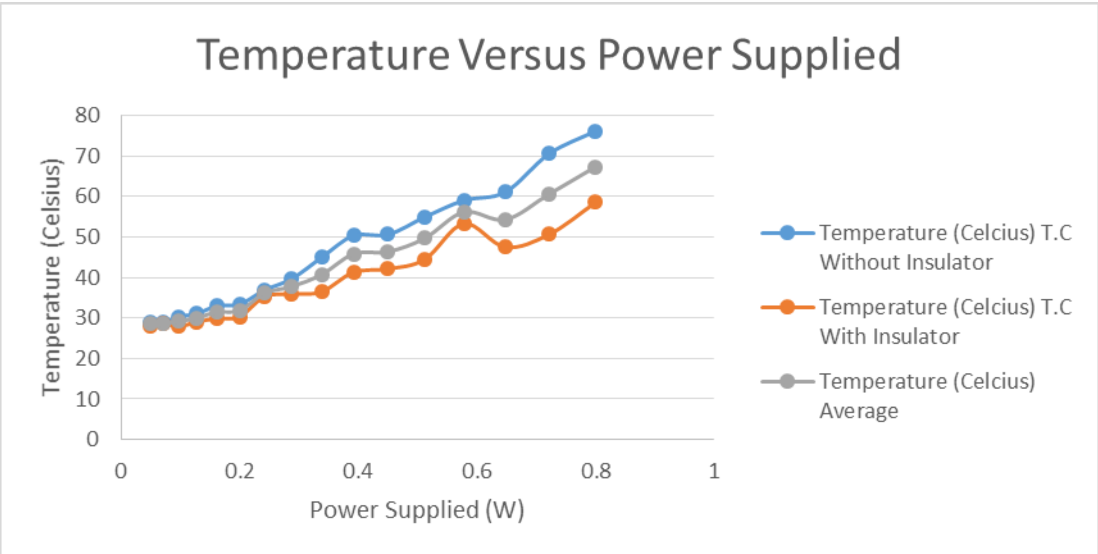

Figure 4.2: Summary of the temperature profile of the heater.

From Figure 4.18, the power needed to heat up the heater is very small. Approximately 0.3 W of power supply enables heater heat up the paraffin wax to 40 °C. And at this point, the paraffin starts to melt.

4.2 PDMS Structure

After the PDMS is filled with solid paraffin wax, the PDMS structure is bonded to the heater. Blue colour food dye is then fill into the drug reservoir through the hole punched by belt puncher. At initial condition, the condition of the device is shown in Figure 4.3. The rectangular part is fully filled with paraffin wax and food dye is partially filled inside the drug reservoir. There is no food dye on the surface of the PDMS structure. The visibility of paraffin wax is quite blur.

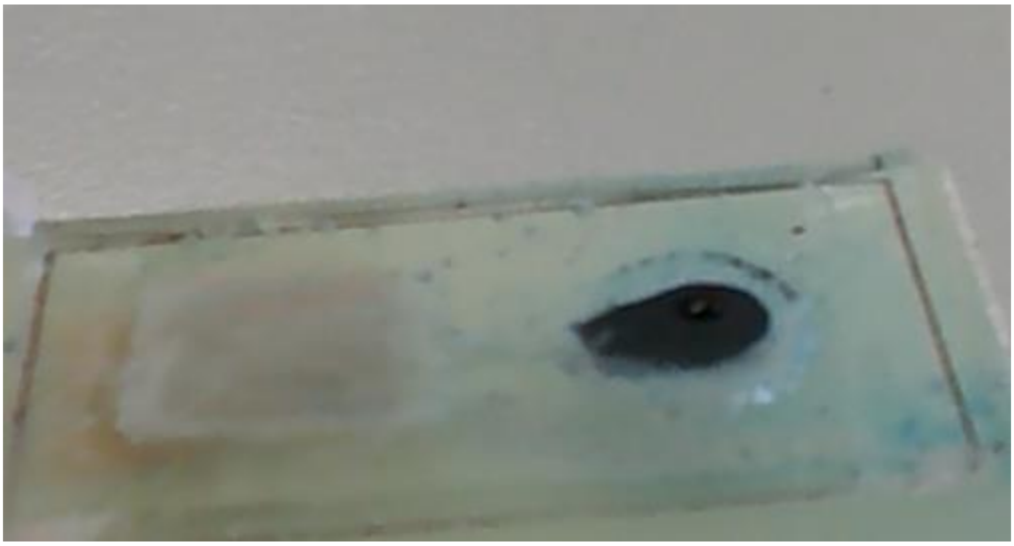

Figure 4.3: Initial condition of drug delivery device.

The current of the power supply had been set to 2.0 A. This is the temperature that the heater gives the temperature reading of approximately 70°C. However, after the heater is connected to the power supply, the time taken for paraffin to actuate is quite long. After 110 seconds, the drug had been expulsed out and the condition is shown in Figure 4.4. The paraffin wax had expanded and flow into the drug reservoir by the thin channel. This creates a very large hydraulic pressure and push the food dye out of the drug reservoir. The observations of the device had been recorded by using a camera. Figure 4.5 show the conditions of the device every 20 seconds. The paraffin wax visibility become clearer as time goes. This shows the melting of paraffin wax. There is also bubble formed inside the rectangular part. This may due to the air trapped inside the rectangular part when the solid paraffin wax is put into it.

Figure 4.4: Drug expulse condition after connected to power supply for 110 seconds.

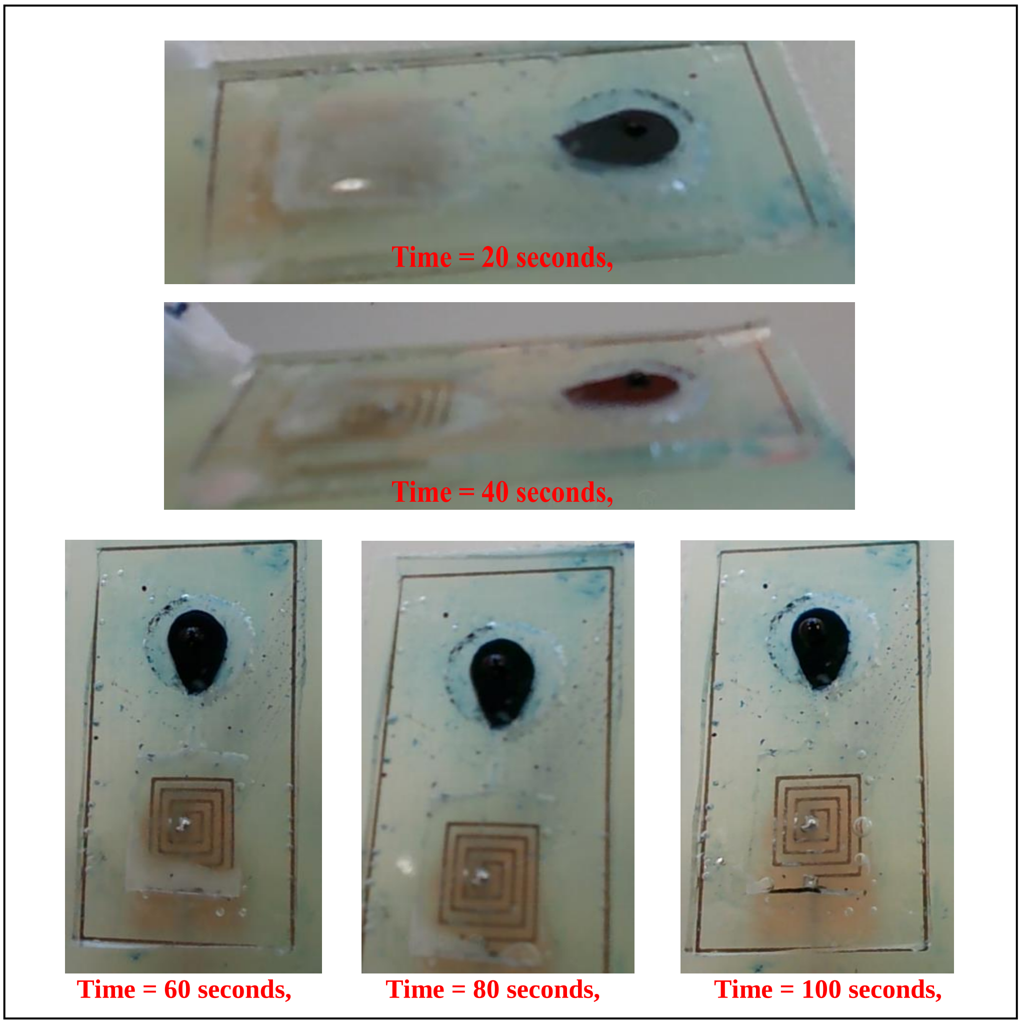

Figure 4.5: Conditions of drug delivery device for every 20 seconds.

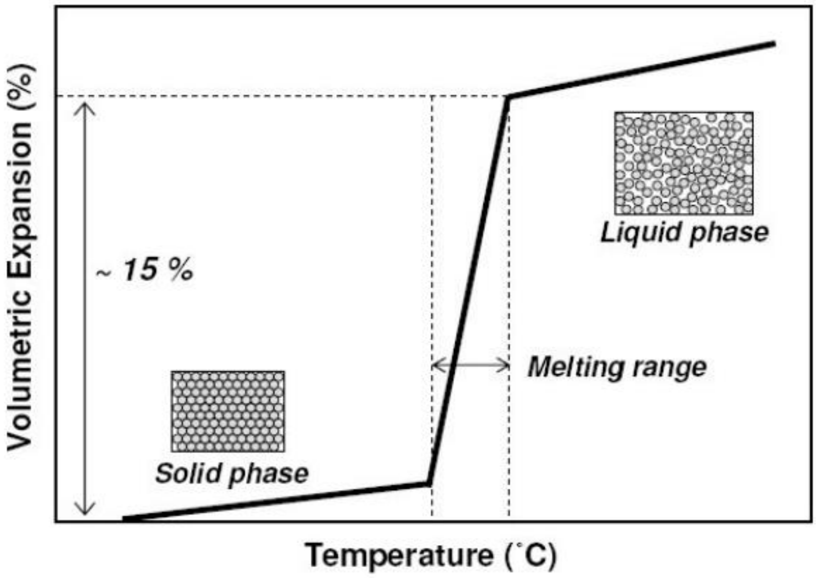

Figure 4.6: Typical volumetric expansion curve of paraffin wax (Lee and Lucyszyn, 2005).

The time taken for the paraffin wax to expand and actuate is quite long. This is because of the properties of paraffin wax stated in Figure 4.6. Paraffin wax, which is a phase change material, has very high latent heat. The time can be said that is one of the major drawbacks of phase change material.

The device proposed is successfully built but the characterization of the device cannot be done due to two major issues. First issue is that the mould that being used is a paper mould which easily deform and create impurities during fabrication. The reason why use this paper mould is that, the 3D printer is under maintainence. If 3D printer can be used to print out the mould with fine dimension, the PDMS structure will be better produced. This issue is also causing the air bubble formed in the rectangular part of PDMS structure when heated up. There is air trapped due to the paraffin did not fully fill up the reactangular part. If using fine mould produced by 3D printer, then the problem of air bubble can be solved as well.

Second issue is the soldering problem occur on the heater on PCB board. The solder does not cover the hole drilled and causing the paraffin wax leak out through the uncovered hole. This issue happens at the early stage of building this device. Some epoxy had been tried to apply to cover the hole but it is not succesful due to the epoxy melts when heated. Then, copper tape had been used to try to cover the hole. However, only one model was succesfully done and copper tape did not help to overcome the issue. The model that was successfully done may be because of the drilled hole is just luckily fully covered by the solder. However, during the second time of using the previously successful model, the paraffin wax leak. The leaking problem of paraffin wax not being solved due to not enough time to figure out the solution on this issue.

The volume expulsed out from the device cannot be measured due to failure to build a succeful model. Among the model that had been built, only 2 of the model succefully functioned. And only one of the model had been recorded down. Thus, the characterization of the PDMS structure had not been done in this project.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The development and characterization of drug delivery device using phase change material are the core of this project. In this project, a new concept of paraffin actuator in drug delivery had been demonstrated. Drug had been expulsed out when paraffin wax actuated. The device is viable to provide dosing or deliver drug. Phase change material with economical price and simplicity of fabrication is worth to be developed. Besides that, low consumption of energy also one of the advantages of using paraffin wax microactuator. Paraffin wax microactuator is well-suited for providing high hydraulic pressure and force. Thus, it can be concluded that paraffin wax, which is one type of the phase change material, is a promising material that create many future possibilities in MEMS and drug delivery.

However, in this project, due to limited time and the two major issues mentioned in Chapter 4.2, which are mould issues and leak issue of paraffin wax, the drug delivery device cannot be fully characterized. Prototypes that built were failed to respond and not well-functioned. Several recommendations had been proposed for future development purposes.

5.2 Recommendations

The uncovered hole that causes paraffin wax to leak when heated up is the major drawback from this project. To overcome this problem, suitable epoxy should be used. Sliver paste is one of the conductive epoxy that are proposed to be used. However, the price of the silver paste is quite expensive and not economical. Thus this epoxy is needed to be concerned during future development. Better soldering equipment may also help to solve this problem.

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APPENDICES

APPENDIX A: Tables and Graphs

Table A1 indicates the results generated from BenchLink at which current rating is 0.5 A and Figure A1 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	26.791	26.765
2	26.861	26.752
3	26.842	26.728
4	27.070	26.678
5	27.729	26.781
6	28.098	26.894
7	28.371	27.007
8	28.548	27.112
9	28.690	27.189
10	28.816	27.265
11	28.913	27.340
12	28.945	27.414
13	28.967	27.478
14	29.130	27.525
15	29.258	27.626
16	29.376	27.685
17	29.379	27.714
18	29.405	27.764
19	29.452	27.798
20	29.433	27.819
21	29.512	27.878
22	29.555	27.949
23	29.630	28.012
24	29.555	27.973
25	29.493	27.968

26	29.418	27.964
27	29.397	27.932
28	29.386	27.943
29	29.343	27.940
30	29.327	27.937
31	29.343	27.977
32	29.335	27.987
33	29.287	28.019
34	29.228	28.011
35	29.233	28.053
36	29.109	28.073
37	29.087	28.099
38	29.098	28.112
39	29.085	28.157
40	29.077	28.144
41	29.095	28.149
42	29.133	28.178
43	29.162	28.191
44	29.117	28.220
45	29.109	28.260
46	29.144	28.273
47	29.154	28.302
48	29.122	28.307
49	29.074	28.339
50	28.769	28.344
51	29.106	28.442
52	29.042	28.455
53	28.940	28.452
54	28.961	28.463
55	28.852	28.352
56	27.130	28.534
57	27.020	28.579
58	29.642	28.623
59	28.988	28.663
60	28.903	28.676

Table A1: Temperature profile of heater at 0.5 A

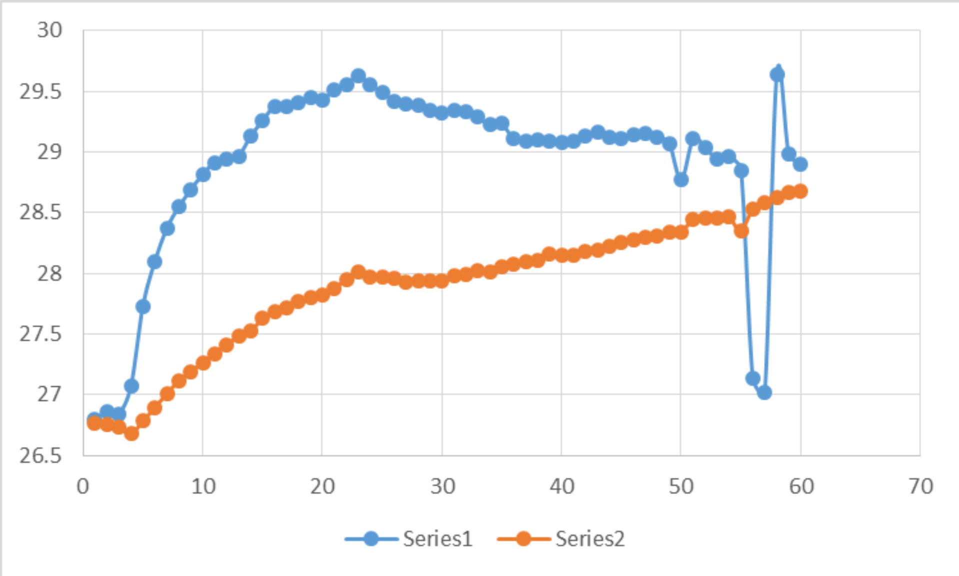

Figure A1: Temperature profile of heater at 0.5 A.

From Figure A1, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 28.93703 °C and 28.15825 °C from thermocouple with insulator. Table A2 indicates the results generated from BenchLink at which current rating is 0.6 A and Figure A2 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	27.792	26.803
2	27.599	26.789
3	27.497	26.752
4	27.524	26.739
5	27.366	26.713
6	27.516	26.747
7	27.735	26.565
8	28.225	26.813
9	28.381	26.987
10	28.624	27.176
11	28.836	27.358
12	28.841	27.572
13	28.882	27.716
14	29.002	27.882
15	29.080	28.019
16	29.165	28.185
17	29.154	28.298
18	29.130	28.364

19	28.764	28.596
20	28.806	28.614
21	28.921	28.728
22	29.036	28.775
23	29.074	28.834
24	29.112	28.863
25	29.120	28.892
26	29.123	28.953
27	29.160	28.968
28	29.190	29.015
29	29.243	29.050
30	29.331	29.123
31	29.390	29.147
32	29.479	29.184
33	29.436	29.139
34	29.409	29.163
35	29.409	29.155
36	29.389	29.143
37	29.335	29.130
38	29.308	29.133
39	29.185	29.061
40	29.121	29.025
41	29.156	29.043
42	29.161	29.038
43	29.175	29.019
44	29.108	28.990
45	29.030	28.964
46	28.995	28.951
47	29.041	28.961
48	29.054	28.959
49	29.014	28.951
50	28.982	28.888
51	29.000	28.914
52	29.041	28.901
53	29.041	28.922
54	29.073	28.932
55	29.089	28.924
56	29.070	28.930
57	29.092	28.927
58	29.094	28.943
59	29.137	28.948
60	29.175	28.951

Table A2: Temperature profile of heater at 0.6A

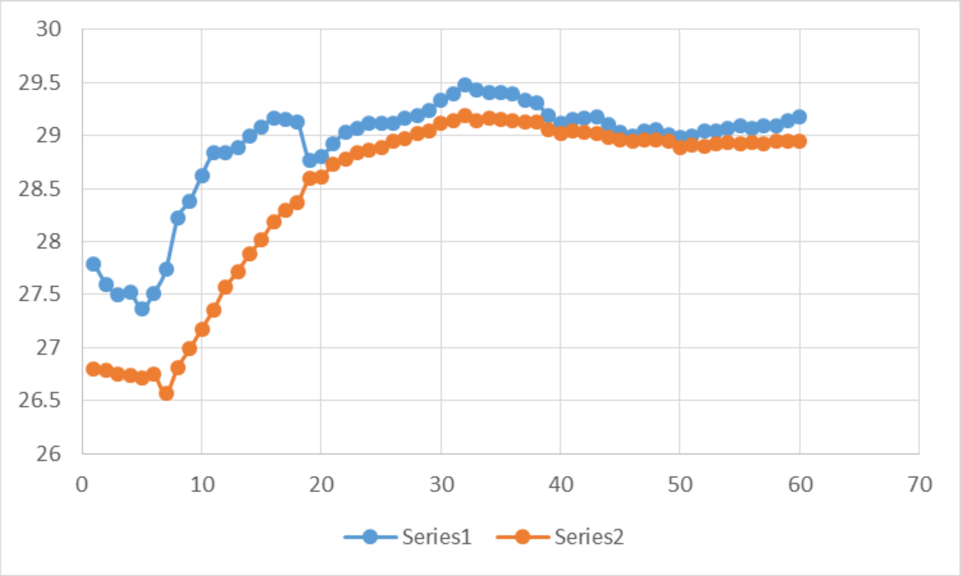

Figure A2: Temperature profile of heater at 0.6A.

From Figure A2, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 28.92645 °C and 28.53268 °C from thermocouple with insulator. Table A3 indicates the results generated from BenchLink at which current rating is 0.7 A and Figure A3 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	26.018	25.760
2	25.908	25.750
3	25.959	25.768
4	25.855	25.771
5	25.852	25.776
6	25.836	25.779
7	25.844	25.800
8	26.345	25.809
9	27.120	25.938
10	27.880	26.144
11	28.231	26.394
12	28.384	26.589
13	28.662	26.778
14	28.825	26.907
15	29.058	27.031
16	29.303	27.140
17	29.491	27.241
18	29.333	27.240

19	28.952	27.325
20	28.631	27.332
21	28.482	27.579
22	28.905	27.644
23	29.055	27.697
24	29.258	27.752
25	29.416	27.837
26	29.575	27.921
27	29.736	28.031
28	29.824	28.095
29	29.843	28.166
30	29.953	28.221
31	29.978	28.192
32	30.085	28.247
33	30.364	28.430
34	30.633	28.528
35	30.850	28.557
36	30.973	28.633
37	31.048	28.607
38	30.994	28.572
39	31.050	28.533
40	31.077	28.470
41	31.053	28.507
42	31.158	28.464
43	31.318	28.520
44	31.452	28.557
45	31.377	28.493
46	31.326	28.464
47	31.356	28.404
48	31.468	28.428
49	31.591	28.462
50	31.645	28.457
51	31.757	28.483
52	31.763	28.462
53	31.835	28.451
54	31.918	28.525
55	32.073	28.554
56	32.253	28.596
57	32.365	28.651
58	32.445	28.707
59	32.424	28.715
60	32.285	28.636

Table A3: Temperature profile of heater at 0.7A

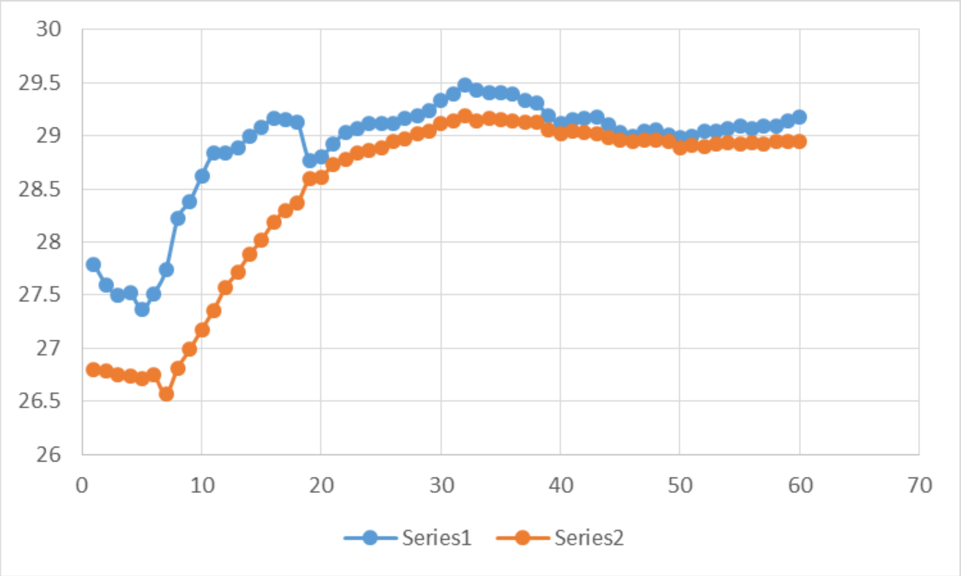

Figure A3: Temperature profile of heater at 0.7A.

From Figure A3, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 30.33898 °C and 27.93919 °C from thermocouple with insulator. Table A4 indicates the results generated from BenchLink at which current rating is 0.8 A and Figure A4 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	26.376	26.407
2	26.421	26.375
3	26.319	26.401
4	26.477	26.499
5	27.896	26.546
6	28.678	26.815
7	29.265	27.086
8	29.530	27.315
9	29.972	27.481
10	30.336	27.537
11	30.684	27.766
12	30.879	27.947
13	31.128	28.166
14	31.594	28.366
15	32.009	28.545
16	32.124	28.651
17	32.237	28.714
18	32.277	28.782

19	32.242	28.827
20	32.328	28.953
21	32.333	29.030
22	32.299	29.067
23	32.341	29.122
24	32.395	29.220
25	32.325	29.264
26	30.392	29.264
27	31.993	29.312
28	31.945	29.341
29	31.980	29.404
30	32.044	29.380
31	32.181	29.391
32	32.293	29.433
33	32.398	29.512
34	32.550	29.604
35	32.601	29.562
36	32.561	29.509
37	32.221	29.507
38	31.477	29.493
39	31.667	29.546
40	31.503	29.583
41	31.546	29.651
42	31.551	29.715
43	31.418	29.680
44	31.372	29.744
45	31.324	29.730
46	31.236	29.730
47	31.158	29.736
48	31.217	29.833
49	31.227	29.867
50	31.337	29.978
51	31.423	30.052
52	31.402	30.007
53	31.431	29.981
54	31.300	29.957
55	31.273	29.910
56	31.369	29.965
57	31.482	30.020
58	31.578	30.085
59	31.638	30.085
60	31.566	30.098

Table A4: Temperature profile of heater at 0.8A

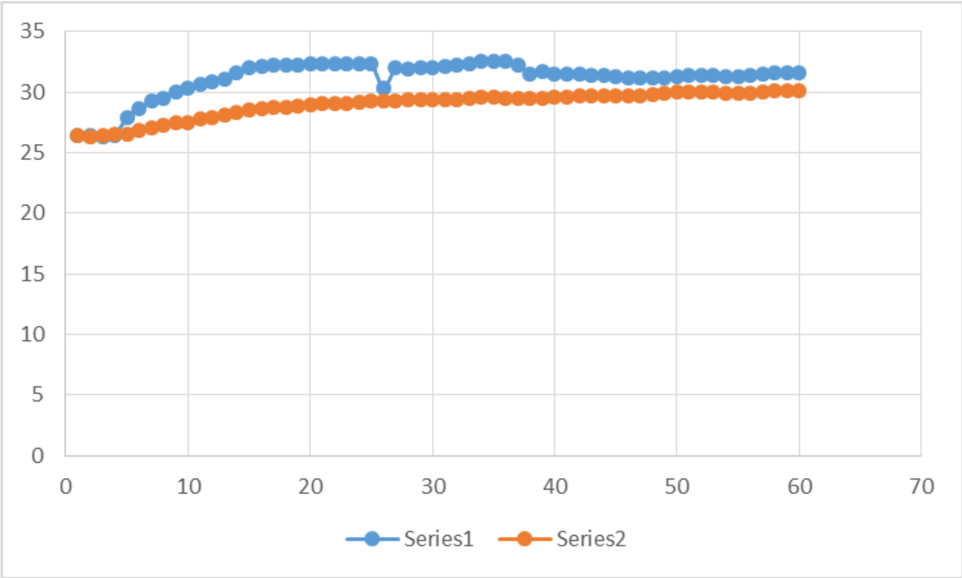

Figure A4: Temperature profile of heater at 0.8A.

From Figure A4, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 31.08923 °C and 29.02377 °C from thermocouple with insulator. Table A5 indicates the results generated from BenchLink at which current rating is 0.9 A and Figure A5 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	26.411	27.083
2	26.379	27.054
3	26.427	27.153
4	26.404	27.019
5	27.796	27.171
6	29.764	27.501
7	30.942	27.906
8	31.789	28.196
9	32.429	28.475
10	32.932	28.786
11	33.385	29.076
12	33.805	29.255
13	34.124	29.410
14	34.223	29.521
15	34.346	29.586
16	34.429	29.710
17	34.520	29.810
18	34.560	29.850

19	34.573	29.947
20	34.667	30.068
21	34.699	30.129
22	34.713	30.250
23	34.705	30.306
24	34.332	30.334
25	33.684	30.385
26	34.016	30.493
27	34.156	30.601
28	34.172	30.608
29	34.164	30.619
30	34.190	30.637
31	34.217	30.653
32	34.330	30.745
33	33.869	30.706
34	33.802	30.777
35	34.083	30.903
36	34.078	30.845
37	34.161	30.956
38	34.265	31.054
39	34.182	30.914
40	34.089	30.874
41	34.111	30.881
42	34.063	30.868
43	34.028	30.852
44	33.750	30.894
45	33.809	30.978
46	33.838	30.999
47	33.758	31.026
48	33.852	31.097
49	33.762	31.039
50	32.782	30.768
51	31.881	30.536
52	31.182	30.294
53	30.644	30.091

Table A5: Temperature profile of heater at 0.9A

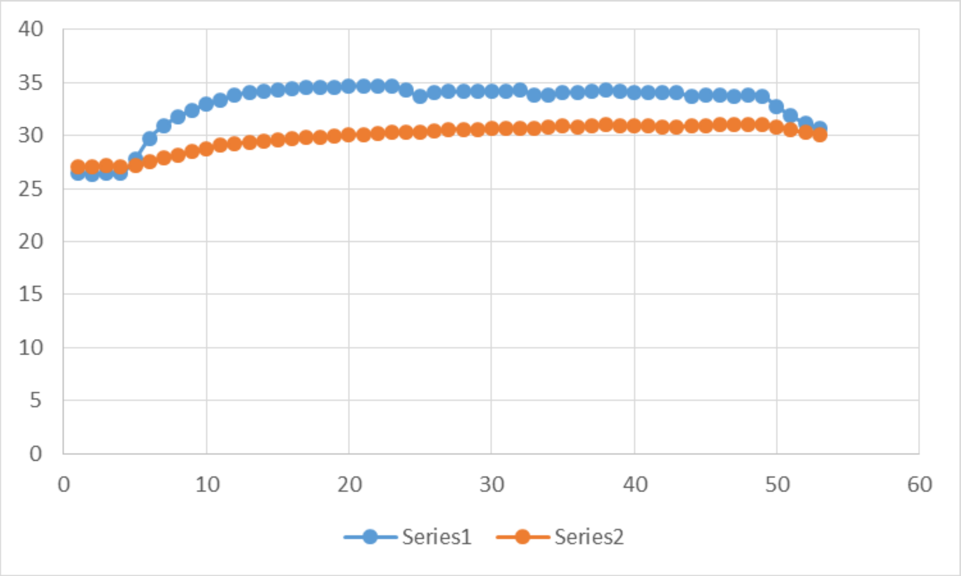

Figure A5: Temperature profile of heater at 0.9A.

From Figure A5, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 33.00573 °C and 29.91866 °C from thermocouple with insulator. Table A6 indicates the results generated from BenchLink at which current rating is 0.7 A and Figure A6 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	26.040	26.041
2	26.043	26.033
3	26.094	26.044
4	27.933	26.273
5	29.655	26.744
6	30.486	27.204
7	30.949	27.501
8	31.367	27.865
9	31.844	28.105
10	32.443	28.381
11	33.083	28.752
12	32.165	29.158
13	32.484	28.990
14	33.212	29.032
15	33.675	29.153
16	34.307	29.263
17	34.104	29.395
18	34.146	29.514

19	34.203	29.680
20	34.334	29.824
21	34.377	29.993
22	34.401	30.122
23	34.363	30.22
24	34.323	30.225
25	34.310	30.301
26	34.390	30.399
27	34.468	30.438
28	34.404	30.496
29	35.377	30.594
30	34.404	30.607
31	34.395	30.686
32	34.470	30.838
33	34.484	30.910
34	34.476	30.949
35	34.420	31.020
36	34.389	31.056
37	34.415	31.079
38	34.456	31.157
39	34.366	31.165
40	34.259	31.189
41	34.289	31.224
42	34.257	31.232
43	34.319	31.286
44	34.332	31.354
45	34.493	31.520
46	34.581	31.576
47	34.632	31.655
48	34.589	31.707
49	34.557	31.697
50	34.420	31.631
51	34.335	31.581
52	34.220	31.531
53	34.201	31.531
54	34.182	31.581
55	34.163	31.620
56	34.292	31.707
57	34.313	31.742
58	34.284	31.710
59	34.279	31.692
60	34.230	31.676

Table A6: Temperature profile of heater at 1.0A

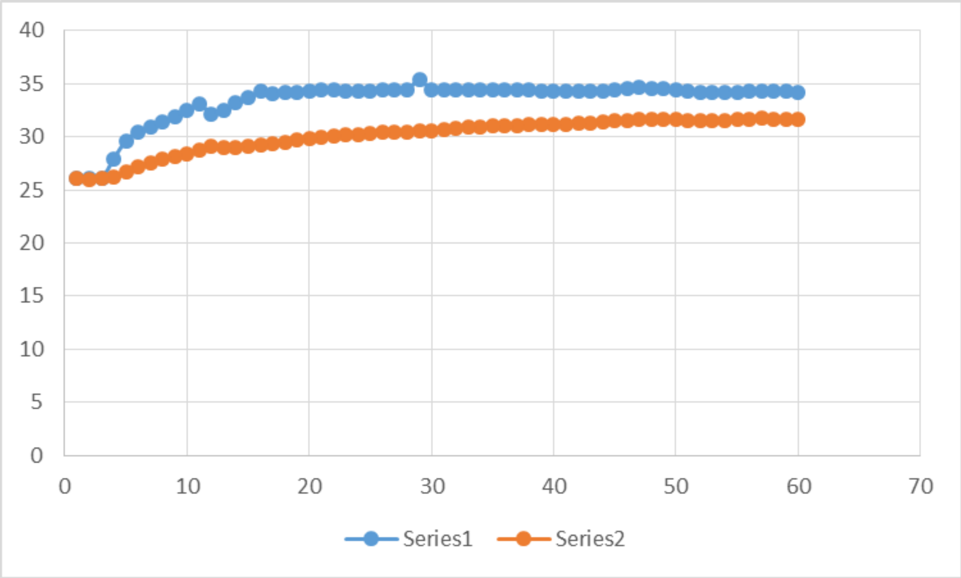

Figure A6: Temperature profile of heater at 1.0A.

From Figure A6, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 33.38944 °C and 30.30086 °C from thermocouple with insulator. Table A7 indicates the results generated from BenchLink at which current rating is 1.1 A and Figure A7 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	26.655	27.087
2	26.620	27.237
3	26.660	27.192
4	26.679	27.171
5	26.794	27.248
6	26.885	27.342
7	29.011	27.514
8	30.754	27.940
9	32.302	28.409
10	33.113	28.836
11	33.828	29.239
12	34.503	29.642
13	35.073	29.979
14	35.531	30.274
15	35.859	30.513
16	36.179	30.772
17	36.394	31.003
18	36.597	31.172

19	36.753	31.372
20	36.981	31.549
21	37.158	31.733
22	37.312	31.844
23	37.367	32.015
24	37.357	32.099
25	37.259	32.123
26	37.370	32.254
27	37.481	32.389
28	37.616	32.497
29	37.603	32.565
30	37.664	32.726
31	37.841	32.894
32	38.064	33.045
33	38.278	33.195
34	38.442	33.350
35	38.479	33.413
36	38.495	33.437
37	38.564	33.524
38	38.601	33.592
39	38.701	33.706
40	38.810	33.819
41	38.886	33.958
42	38.857	34.043
43	38.979	34.139
44	39.176	34.297
45	39.277	34.523
46	39.225	34.501
47	38.201	34.711
48	37.806	34.867
49	38.157	34.930
50	39.824	35.019
51	38.019	35.126
52	38.307	35.200
53	38.532	35.247
54	36.777	35.394
55	38.545	35.331
56	38.426	35.400
57	38.482	35.455
58	38.172	35.580
59	37.850	35.620
60	37.631	35.678

Table A7: Temperature profile of heater at 1.1A

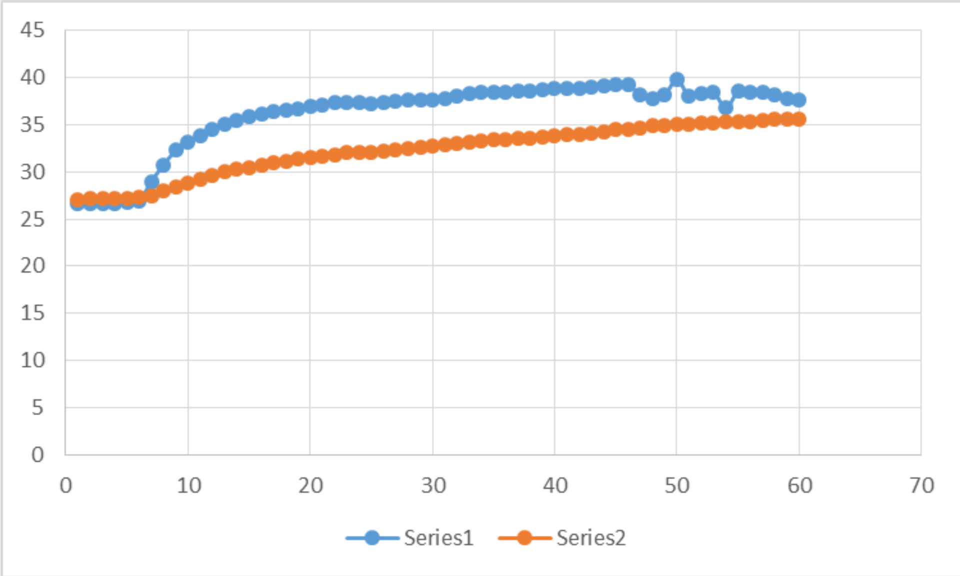

Figure A7: Temperature profile of heater at 1.1A.

From Figure A7, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 36.89316 °C and 35.3134 °C from thermocouple with insulator. Table A8 indicates the results generated from BenchLink at which current rating is 1.2 A and Figure A8 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	30.212	29.382
2	30.024	29.324
3	29.778	29.253
4	29.573	29.295
5	29.587	29.227
6	32.753	29.494
7	35.122	30.181
8	37.207	30.742
9	38.610	31.387
10	39.721	32.030
11	40.445	32.548
12	41.057	33.027
13	41.530	33.490
14	41.959	33.791
15	41.980	34.120
16	41.999	34.323
17	41.525	34.655
18	40.755	34.749

19	40.226	34.931
20	39.847	35.081
21	39.455	35.192
22	39.114	35.218
23	38.974	35.308
24	38.900	35.397
25	38.831	35.529
26	38.749	35.640
27	38.757	35.750
28	39.633	36.085
29	39.349	36.187
30	40.773	36.385
31	41.237	36.345
32	40.427	36.548
33	40.437	36.609
34	40.353	36.698
35	40.591	36.747
36	40.764	36.825
37	40.994	36.902
38	41.129	36.987
39	41.236	37.025
40	41.445	37.149
41	41.590	37.199
42	41.600	37.222
43	41.796	37.310
44	41.964	37.457
45	42.117	37.575
46	42.251	37.689
47	42.368	37.738
48	42.508	37.817
49	42.590	37.933
50	42.675	38.061
51	42.587	38.187
52	42.669	38.287
53	42.804	38.364
54	42.952	38.408
55	43.127	38.516
56	43.122	38.570
57	43.148	38.685
58	43.222	38.724
59	43.172	38.639
60	42.503	38.626

Table A8: Temperature profile of heater at 1.2A

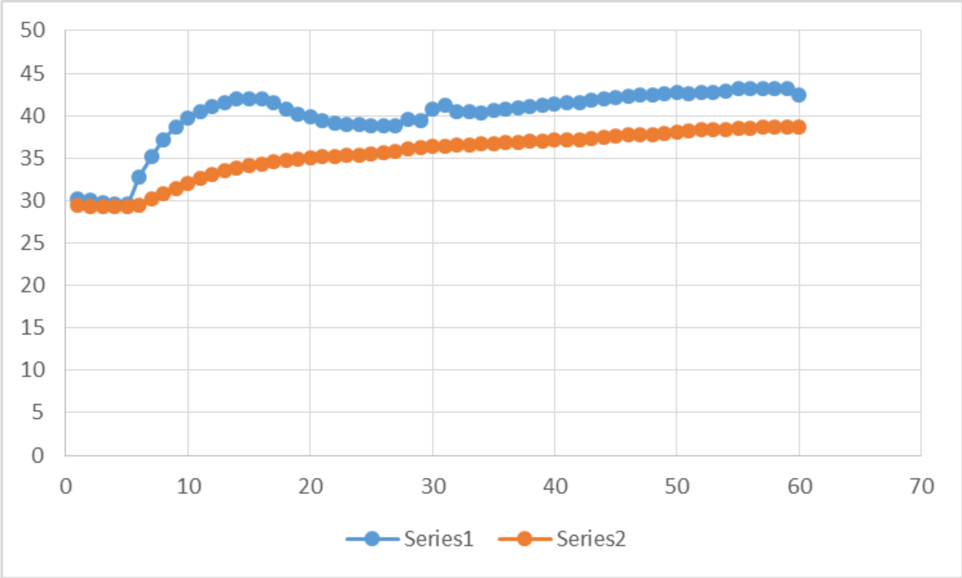

Figure A8: Temperature profile of heater at 1.2A.

From Figure A8, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 39.68984 °C and 35.89765 °C from thermocouple with insulator. Table A9 indicates the results generated from BenchLink at which current rating is 1.3 A and Figure A9 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	28.330	29.439
2	28.271	29.384
3	28.196	29.289
4	28.142	29.197
5	28.547	29.099
6	31.568	29.461
7	33.766	30.080
8	35.862	30.703
9	37.310	31.309
10	38.552	31.841
11	39.577	32.384
12	40.241	32.782
13	40.607	33.175
14	41.043	33.520
15	41.401	33.930
16	41.747	34.310
17	42.311	34.626
18	42.809	34.913

19	43.187	35.139
20	43.423	35.405
21	43.727	35.621
22	44.039	35.808
23	44.246	35.964
24	44.468	36.103
25	44.598	36.253
26	44.667	36.356
27	44.561	36.411
28	44.449	36.488
29	44.484	36.527
30	44.516	36.567
31	44.688	36.604
32	44.794	36.680
33	44.876	36.750
34	44.989	36.832
35	46.572	36.911
36	47.467	36.994
37	47.673	37.109
38	47.858	37.155
39	48.498	37.258
40	48.637	37.312
41	48.241	37.392
42	48.325	37.471
43	48.207	37.551
44	48.516	37.589
45	47.083	37.605
46	47.694	37.556
47	48.102	37.499
48	47.932	37.445
49	47.797	37.456
50	48.050	37.435
51	48.553	37.415
52	48.954	37.425
53	49.080	37.445
54	48.438	37.384
55	47.821	37.335
56	47.475	37.253
57	47.202	37.189
58	46.744	37.071
59	46.307	36.981
60	45.961	36.911

Table A9: Temperature profile of heater at 1.3A

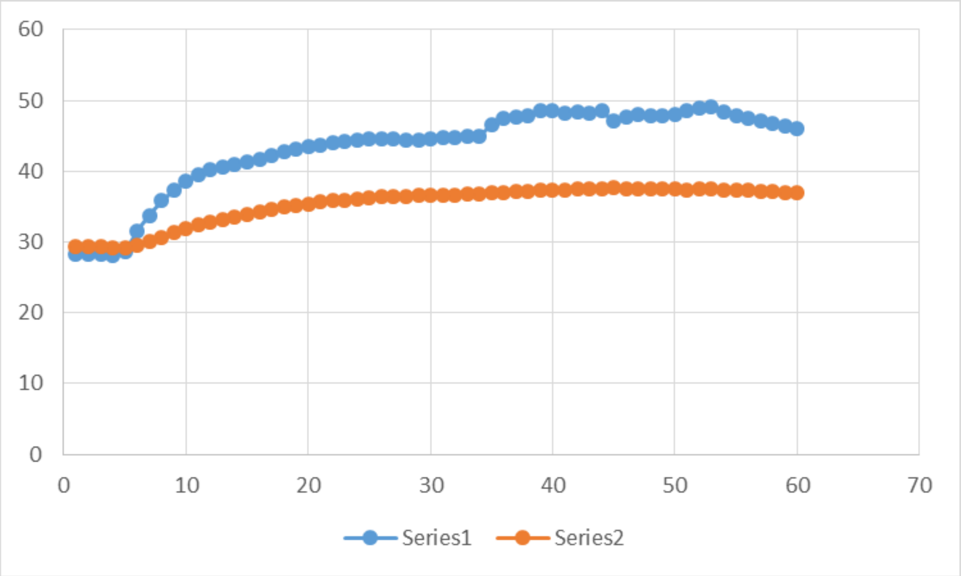

Figure A9: Temperature profile of heater at 1.3A.

From Figure A9, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 44.93352 °C and 36.47705 °C from thermocouple with insulator. Table A10 indicates the results generated from BenchLink at which current rating is 1.4 A and Figure A10 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	28.523	29.033
2	28.443	28.977
3	28.33	28.952
4	28.235	28.842
5	28.283	28.926
6	33.016	29.459
7	35.265	30.595
8	37.51	31.219
9	39.378	31.769
10	40.778	32.449
11	42.038	33.057
12	43.099	33.666
13	43.301	34.25
14	44.722	34.914
15	43.864	35.504
16	44.899	36.036
17	45.299	36.305
18	45.418	36.289

19	45.934	36.284
20	46.117	36.471
21	46.172	36.725
22	46.474	37.015
23	46.641	37.287
24	47.138	37.547
25	47.316	37.803
26	47.464	38.037
27	47.461	38.178
28	47.485	38.361
29	47.58	38.512
30	47.196	38.725
31	46.519	38.9
32	46.172	39.074
33	46.056	39.246
34	45.876	39.393
35	45.722	39.624
36	45.455	39.608
37	45.452	39.503
38	45.616	39.601
39	45.825	39.78
40	45.971	40.022
41	46.143	40.065
42	46.069	40.271
43	46.717	40.34
44	46.455	40.569
45	47.186	40.671
46	47.482	40.754
47	47.689	40.807
48	48.149	40.838
49	48.443	40.882
50	48.674	40.995
51	48.875	41.103
52	49.009	41.229
53	49.19	41.329
54	49.468	41.426
55	49.694	41.557
56	49.835	41.632
57	50.037	41.727
58	50.218	41.752
59	50.292	41.824
60	50.444	41.819

Table A10: Temperature profile of heater at 1.4A

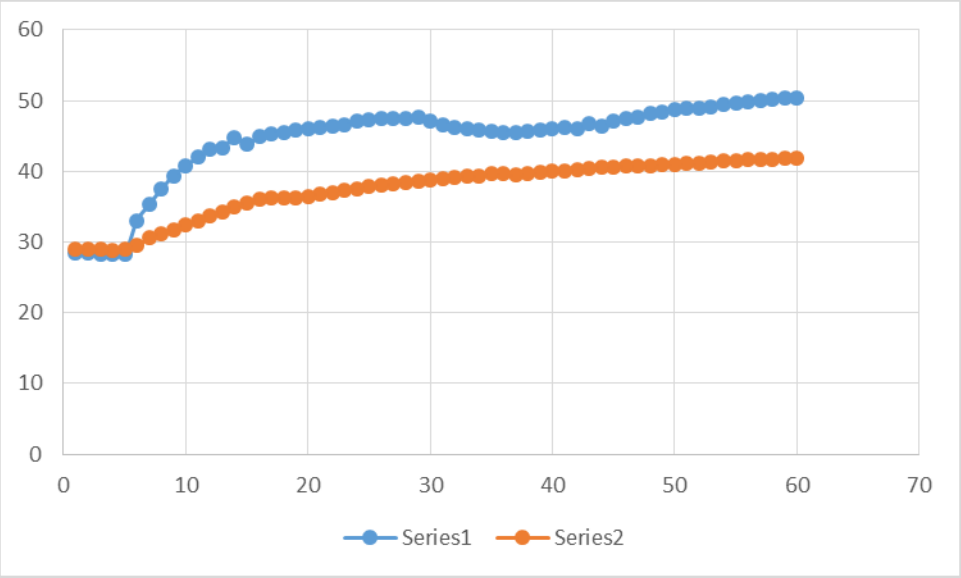

Figure A10: Temperature profile of heater at 1.4A.

From Figure A10, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 50.32087 °C and 41.27352 °C from thermocouple with insulator. Table A11 indicates the results generated from BenchLink at which current rating is 1.5 A and Figure A11 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	29.836	29.570
2	29.766	29.470
3	29.638	29.375
4	29.520	29.447
5	29.504	29.233
6	29.354	29.223
7	29.333	29.146
8	29.330	29.125
9	32.963	29.315
10	35.788	29.578
11	40.364	30.471
12	44.019	31.417
13	46.528	32.483
14	47.972	33.458
15	48.648	34.245
16	48.853	35.009
17	50.025	35.681
18	51.043	36.358

19	51.105	36.995
20	51.779	37.496
21	52.023	37.937
22	52.272	38.297
23	52.587	38.697
24	52.050	39.039
25	52.529	39.406
26	52.661	39.714
27	52.474	40.007
28	53.007	40.294
29	53.450	40.564
30	53.835	40.782
31	54.008	41.013
32	53.883	41.175
33	53.623	41.208
34	53.266	41.267
35	53.185	41.452
36	53.030	41.668
37	52.920	41.902
38	52.855	42.048
39	52.417	42.228
40	52.207	42.377
41	52.503	42.585
42	52.729	42.718
43	52.897	42.932
44	52.956	43.038
45	52.956	43.187
46	53.065	43.311
47	53.296	43.432
48	52.898	43.538
49	50.675	43.682
50	47.880	43.952
51	46.140	43.375
52	44.615	42.638
53	44.525	41.937
54	46.089	41.935
55	46.957	42.286
56	47.691	42.633
57	48.030	42.967
58	48.303	43.326
59	48.560	43.468
60	48.770	43.647

Table A11: Temperature profile of heater at 1.5A

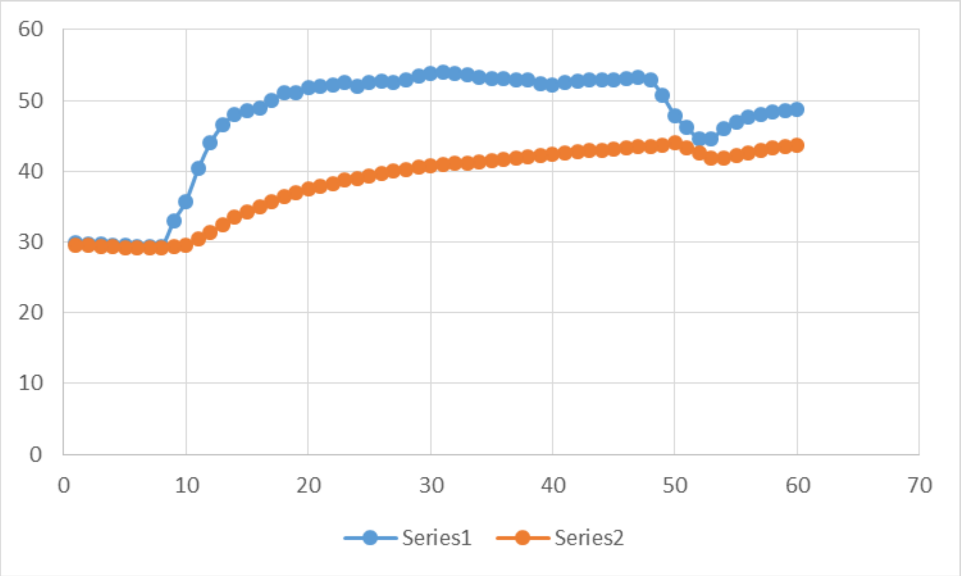

Figure A11: Temperature profile of heater at 1.5A.

From Figure A11, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 50.59915 °C and 42.13878 °C from thermocouple with insulator. Table A12 indicates the results generated from BenchLink at which current rating is 1.6 A and Figure A12 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	27.737	28.166
2	27.742	28.216
3	27.767	28.226
4	27.758	28.240
5	28.674	28.498
6	32.118	28.503
7	34.894	29.277
8	36.439	30.293
9	40.037	30.822
10	42.715	31.354
11	44.402	31.924
12	44.918	32.648
13	44.913	33.291
14	45.076	33.933
15	45.325	34.400
16	45.553	34.909
17	46.046	35.178
18	46.675	35.437

19	47.100	35.835
20	47.047	36.322
21	47.137	36.786
22	47.153	37.179
23	47.127	37.62
24	47.127	38.054
25	46.994	38.503
26	47.156	38.889
27	48.350	39.251
28	48.093	39.312
29	48.641	39.343
30	49.055	39.546
31	49.423	39.628
32	49.548	39.767
33	49.533	40.195
34	49.389	40.863
35	49.446	41.405
36	49.538	41.615
37	49.533	41.834
38	50.120	42.180
39	50.414	42.606
40	51.444	42.527
41	52.341	42.570
42	53.042	42.599
43	53.694	42.714
44	54.253	42.958
45	54.332	43.069
46	54.679	43.173
47	54.813	43.049
48	55.225	42.947
49	55.589	42.929
50	27.737	28.166
51	27.742	28.216
52	27.767	28.226
53	27.758	28.240
54	28.674	28.498
55	32.118	28.503
56	34.894	29.277
57	36.439	30.293
58	40.037	30.822
59	42.715	31.354
60	44.402	31.924

Table A12: Temperature profile of heater at 1.6A

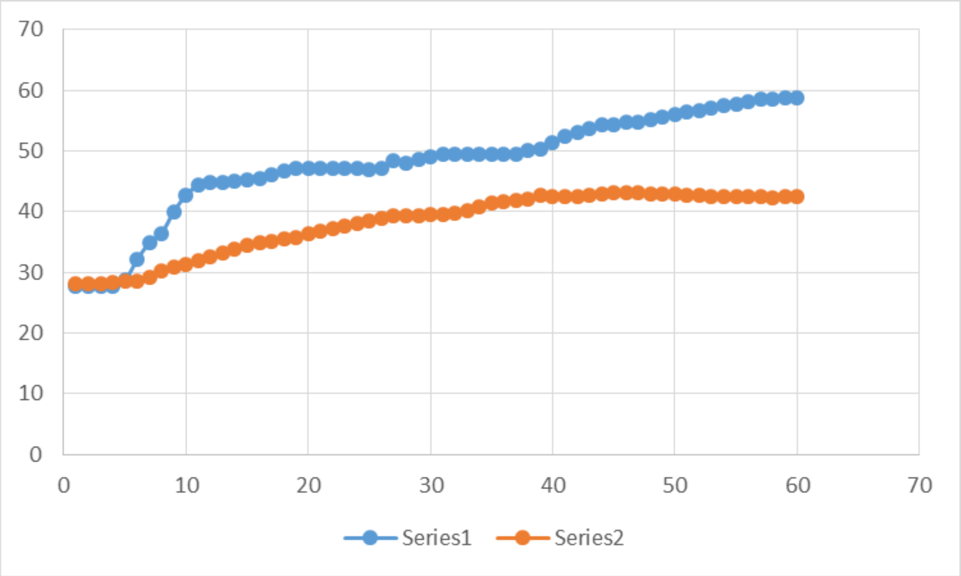

Figure A12: Temperature profile of heater at 1.6A.

From Figure A12, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 54.90248°C and 44.4553°C from thermocouple with insulator. Table A13 indicates the results generated from BenchLink at which current rating is 1.7A and Figure A13 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	30.959	32.412
2	30.694	32.154
3	30.381	32.019
4	30.276	31.796
5	30.547	32.291
6	31.243	33.292
7	32.188	34.545
8	37.282	35.672
9	39.979	36.943
10	42.400	38.052
11	46.103	38.924
12	48.618	39.743
13	50.307	40.391
14	51.628	40.987
15	52.625	41.526
16	53.326	42.043
17	53.811	42.493
18	54.291	42.998

19	54.594	43.455
20	54.940	43.884
21	55.332	44.301
22	55.529	44.722
23	56.412	45.172
24	56.473	44.753
25	57.519	44.140
26	57.980	43.924
27	58.196	44.116
28	58.652	44.473
29	58.736	44.794
30	59.098	44.802
31	59.491	44.925
32	59.758	45.079
33	59.997	45.303
34	60.112	45.475
35	60.251	45.603
36	60.380	45.711
37	60.566	45.850
38	60.944	45.965
39	61.171	46.122
40	61.328	46.286
41	61.503	46.399
42	61.704	46.525
43	61.834	46.683
44	61.846	46.847
45	61.971	46.963
46	61.980	47.085
47	61.930	47.138
48	61.985	47.212
49	62.054	47.304
50	62.033	47.422
51	62.213	47.523
52	62.263	47.760
53	62.237	47.973
54	62.208	48.114
55	62.098	48.194
56	62.083	48.201
57	61.861	48.027
58	61.939	47.965
59	62.153	48.042
60	62.294	48.191

Table A13: Temperature profile of heater at 1.7A

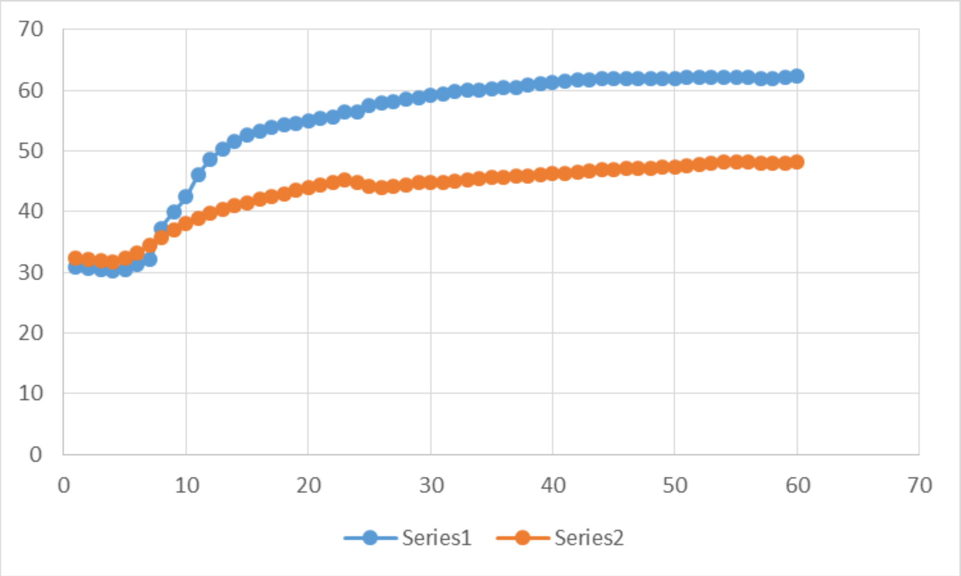

Figure A13: Temperature profile of heater at 1.7A.

From Figure A13, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 59.02351 °C and 53.29914 °C from thermocouple with insulator. Table A14 indicates the results generated from BenchLink at which current rating is 1.8 A and Figure A14 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	30.609	31.907
2	30.497	31.764
3	30.146	31.564
4	30.473	31.417
5	30.460	31.298
6	31.956	31.793
7	36.912	33.102
8	40.702	34.744
9	43.781	36.180
10	45.888	37.487
11	46.947	38.573
12	49.087	39.587
13	51.088	40.446
14	52.494	40.918
15	53.790	41.339
16	54.473	41.815
17	55.545	42.095
18	56.516	42.544

19	57.111	43.220
20	57.727	43.569
21	58.370	43.896
22	59.180	44.230
23	59.807	44.577
24	60.410	44.933
25	60.948	45.221
26	61.590	45.475
27	62.091	45.758
28	62.529	46.022
29	62.936	46.281
30	63.346	46.543
31	63.643	46.815
32	63.925	47.080
33	63.690	47.298
34	63.946	46.844
35	62.297	46.410
36	63.186	46.533
37	61.942	46.839
38	61.214	47.139
39	60.721	47.717
40	60.776	47.873
41	60.656	47.904
42	60.515	48.151
43	60.533	48.220
44	60.627	48.572
45	63.267	48.775
46	64.803	48.701
47	65.267	48.208
48	66.731	47.893
49	67.126	47.777
50	66.964	48.077
51	66.979	48.430
52	67.534	48.708
53	67.626	49.027
54	67.296	49.392
55	67.223	49.686
56	66.715	50.005
57	67.289	50.143
58	65.103	50.314
59	63.978	50.542
60	62.551	50.542

Table A14: Temperature profile of heater at 1.8A

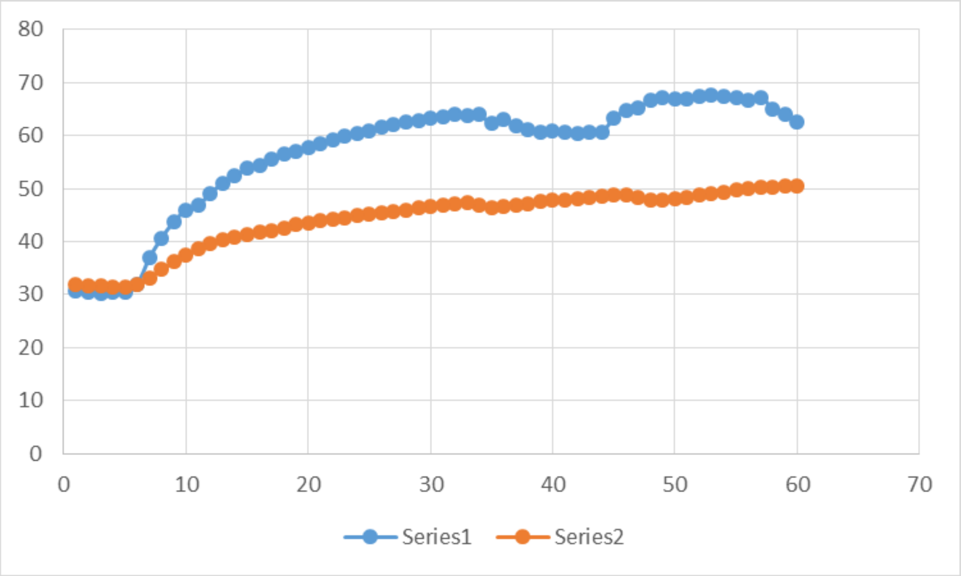

Figure A14: Temperature profile of heater at 1.8A.

From Figure A14, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 61.09393 °C and 47.4795 °C from thermocouple with insulator. Table A15 indicates the results generated from BenchLink at which current rating is 1.9 A and Figure A15 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	30.366	31.233
2	30.302	31.117
3	30.216	30.980
4	30.235	30.806
5	30.120	30.717
6	11.517	30.720
7	60.625	30.862
8	51.677	31.973
9	58.860	33.024
10	64.204	34.757
11	65.506	36.251
12	67.502	37.440
13	68.765	38.644
14	69.469	39.941
15	70.028	41.024
16	70.632	41.886
17	70.911	42.617
18	71.091	43.121

19	71.322	43.455
20	71.496	43.632
21	71.341	43.914
22	71.448	44.268
23	71.302	44.526
24	71.075	44.827
25	70.631	45.161
26	70.456	45.669
27	70.475	46.195
28	70.516	46.575
29	70.506	46.973
30	70.514	47.392
31	55.564	47.990
32	70.135	48.023
33	71.401	48.175
34	70.657	48.373
35	71.263	48.842
36	71.902	49.187
37	72.032	49.224
38	71.972	49.320
39	72.043	49.285
40	72.071	49.302
41	72.131	49.312
42	72.014	49.367
43	71.842	49.463
44	71.79	49.545
45	73.376	49.603
46	73.245	49.829
47	74.101	50.150
48	75.337	50.661
49	73.313	51.140
50	71.625	51.263
51	70.259	51.312
52	69.354	51.389
53	72.665	51.476
54	71.914	51.599
55	71.562	51.782
56	71.853	52.003
57	71.973	52.259
58	72.296	52.574
59	72.714	52.847
60	72.938	53.073

Table A15: Temperature profile of heater at 1.9A

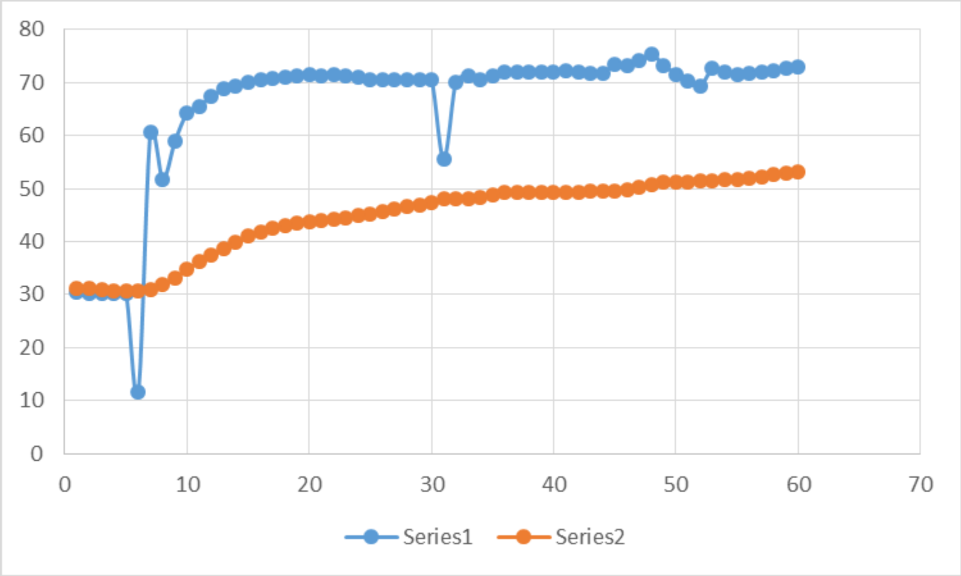

Figure A15: Temperature profile of heater at 1.9A.

From Figure A15, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 70.57438 °C and 50.64763 °C from thermocouple with insulator. Table A16 indicates the results generated from BenchLink at which current rating is 2.0 A and Figure A16 shows the graph of this results.

Time (second)	Temperature (°C)	
	Thermocouple without insulator	Thermocouple with insulator
1	32.839	33.370
2	32.595	33.199
3	32.306	32.962
4	32.697	32.775
5	37.379	32.801
6	47.140	34.034
7	52.507	36.167
8	56.026	37.677
9	61.583	39.043
10	65.369	40.789
11	65.885	42.378
12	66.488	43.762
13	67.166	45.192
14	67.774	46.645
15	68.390	47.703
16	68.487	48.625
17	68.573	49.484
18	68.954	50.340

19	69.156	51.297
20	69.229	52.100
21	69.392	52.962
22	69.462	53.717
23	69.387	54.360
24	68.090	54.869
25	69.397	54.939
26	70.074	55.028
27	72.313	55.419
28	74.597	56.106
29	74.270	56.808
30	74.320	57.352
31	74.279	57.968
32	74.318	58.564
33	74.409	59.081
34	74.219	59.537
35	73.977	60.109
36	73.904	60.555
37	73.969	60.763
38	74.037	60.989
39	73.885	61.102
40	73.758	61.232
41	73.930	61.563
42	74.730	61.899
43	74.117	61.945
44	76.177	61.820
45	78.406	61.339
46	79.885	60.976
47	80.641	60.961
48	80.039	61.019
49	80.349	61.144
50	80.002	61.249
51	79.999	61.406
52	79.874	61.597
53	78.886	61.695
54	72.954	61.943
55	74.443	62.124
56	77.634	62.329
57	79.272	62.469
58	79.814	62.646
59	80.411	62.634
60	80.745	62.739

Table A16: Temperature profile of heater at 2.0A

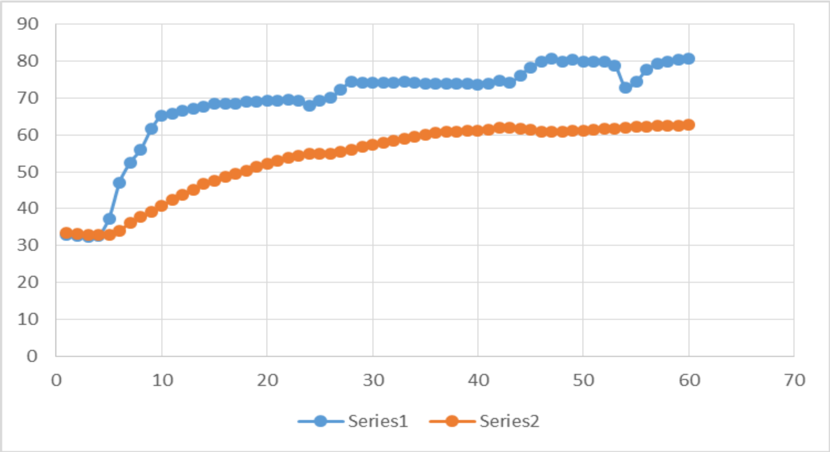

Figure A16: Temperature profile of heater at 2.0A.

From Figure A16, Series 1 represents the temperature reading from thermocouple without insulator. Series 2 represents the temperature reading from thermocouple with insulator. The average temperature calculated from thermocouple without insulator is 76.13398 °C and 58.52296 °C from thermocouple with insulator.