STUDY OF IPMC-BASED SENSOR USING FINITE ELEMENT MODELLING

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A project report submitted in partial fulfilment of the requirements for the award of Master of Engineering (Electronic Systems)

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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 **"STUDY OF IPMC-BASED SENSOR USING FINITE ELEMENT MODELLING"** was prepared by **ZAINAL ABAS BIN HASAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Engineering (Electronic Systems) at Universiti Tunku Abdul Rahman.

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I would like also to express deepest gratitude to my parent, who always give the courage and support me along my studies. Finally, I would like to thanks to all my friends who have assisted me either directly or indirectly through this Final Year Project. The moments that we shared together are unforgettable. They have all been a constant source of strength and inspiration. I hope the knowledge that I gathered and the experience I gained from this project will help me to face the real challenge in working experience. May Allah bless all of you.

ABSTRACT

Ionic Polymer Metal Composites (IPMCs) are active materials that are consisted of thin ionic polymer plated with noble metal. IPMCs feature has interesting bidirectional electromechanical coupling. By supplying input voltage, IPMCs strip will be bend. Whereas, the bending of IPMCs strip will produce an output voltage. This research presents the simulation of the IPMCs as a sensor using COMSOL Multiphysics. A rectangular 2D finite element was simulated to identify the sensor characteristic at difference load, difference length and difference thickness. From the simulation, the output of the IPMCs was reduces as a load or the length decreased. However, the output of the IPMCs was increased as the height of the IPMCs deceased. When the 1kPa load is applied on the bottom of the IPMCs layer, IPMCs will produced 0.038V output voltage. Whereas, the IPMCs only produced 0.022V when the 0.5kPa load is applied. In addition, the structure dimension of the IPMCs was also simulated in this research.

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LIST OF SYMBOLS / ABBREVIATIONS

C	cation concentration
μ	cation mobility
D	the diffusion coefficient
F	Faraday’s constant
z	charge number
Vc	the molar volume which quantifies the cation hydrophilicity
P	Solvent pressure
ϕ	electric potential in the polymer
R	gas constant
T	absolute temperature
IPMC	Ionic polymer-metal composites

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Usually, Ionic polymer-metal composites, (IPMCs) consists of an ionic polymer film (Nafion or Flemion) and was plated with noble metals on top and bottom surfaces such as gold or silver (Chen *et al.*, 2009; Hong, Almomani and Montazami, 2017; Yılmaz *et al.*, 2019). In the past decades, IPMCs becomes an attractive research topics in the application of sensors and actuators due to its advantages such as large mechanical flexibility, easy to fabricate, light weight, resilience and able to react with a low electrical signal (Gudarzi, Smolinski and Wang, 2017).

A voltage output can be produced by bending an IPMC membrane while the input voltage is able to bend the IPMC membrane (Paola *et al.*, 2008). However, the characteristics of the IPMC to act as an actuator or sensor will depend on the design structure of the IPMC.

1.2 Importance of the Study

IPMC is a type of the polymer use in the micro-electro mechanical systems (MEMS). In the growing the MEMS application, new type of the materials are involved in research development and some of the factor is by using polymer to replace a silicon.

IPMC is an example of soft material been use in MEMS. It can react either as an actuator or a sensor. However, the stability of the IPMC is hard to control as the solvent contents of the IPMC will lose when operate in high voltage (Bhandari, Lee and Ahn, 2012). Therefore, an additional study was required to identify the factor and properties of IPMC to act as an actuator or sensor.

1.3 Problem Statement

Ionic Polymer Metal Composites (IPMCs) are active materials that exhibit interesting bidirectional electromechanical coupling phenomena: a voltage output was obtained by bending an IPMC strip while the strip will bend by supplying the input voltage (Bonomo *et al.*, 2006). The voltage obtained by bending the strip is a main information for the IPMC to act as a sensor. However, the characteristic of the IPMC bending will provide a difference voltage. Therefore, this research will focus on the simulation of the voltage created from the IPMC bending with a corrugated structure by using COMSOL.

1.4 Aims and Objectives

The main objective for this research are to simulate the output voltage/ a sensor when the IPMC bend. By performing this simulation, the actual structure of IPMC are design and the properties of the IPMC is apply to simulate the IPMC. In addition, a difference load is apply during this simulation to identify the voltage produce by the IPMC.

1.5 Scope and Limitation of the Study

The scope of this study involves a research on identification the properties on IPMC, modelling the IPMC shape, how IPMC can work as a sensor and simulate the IPMC model using COMSOL Multiphysics. The understanding of the properties of IPMC is required to understand how IPMC can act as a sensor. Then, the simulation was completed by identify the output and properties of the IPMC.

As this study only involve simulation work, the properties of the IPMC material was referred to other journals to model the IPMC.

1.6 Contribution of the Study

The main purpose of this research is to understand the characterisation of the IPMC to act as a sensor. The properties of the IPMC to make a large bending deformation under a low voltage supply make it as a smart material (Sadeghipour, Salomon and Neogi, 1992; Bhandari, Lee and Ahn, 2012). However, the stability of the IPMC to be control is still difficult due to some of the chemical properties. Hence, this research will help to clarify the properties of the IPMC in a simulation.

1.7 Outline of the Report

This report consist of five main chapters which include the introduction of the IPMC, literature review of the IPMC, methodology, result, discussion and conclusion. The objective and theory of the IPMC was describe in the introduction and literature review. Whereas, the simulation and result was discuss in the methodology, result, discussion and conclusion.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will cover the explanation of the structure, principle, characteristic and application of the Ionic polymer-metal composites (IPMC). An electroactive polymer (EAP) is a material that able to change the shape or size when response with an external simulation (Fu, McDaid and Aw, 2013). Ionic polymer-metal composites (IPMC) was an ionic type of EAP material which had been used as a sensor or actuator.

2.2 Structure of the IPMC

Usually, IPMC consists of a thin ion-exchange membrane and noble metal on the top and bottom layer of ion-exchange membrane (Nam *et al.*, 2002; Ansaf *et al.*, 2018). Figure 1(a) shows the structure of the IPMC and Figure 1(b) molecular formula of Nafion. In the past decades, IPMCs becomes an attractive research topics in the application of sensor and actuators due to its advantages such as large mechanical flexibility, easy to fabricate, light weight, resilience and able to react with a low electrical signal (Bonomo *et al.*, 2003; Bhandari, Lee and Ahn, 2012). A voltage output can be obtain by bending an IPMC membrane while the input voltage is able to bend the IPMC membrane(Paola *et al.*, 2008). However, the characteristics of the IPMC to act as an actuator or sensor will depend on the structure of the IPMC.

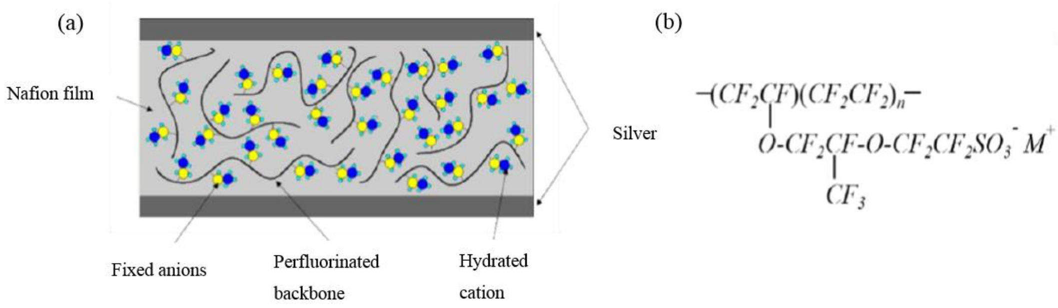

Figure 1: Schematic of the IPMC structure. (a) Nafion film with plated by silver. (b) Molecular formula of Nafion (Zhao et al., 2018).

2.3 Principle and characteristic of the IPMC

Ionic polymer-metal composites (IPMC) are an excellent materials that been use in the micromechanical sensor. The large deformation properties of the IPMC was very useful in a micro robotic systems (Pugal *et al.*, 2010). Theoretically, the structure of the IPMC will impact the capability of the IPMC to act as a sensor or an actuator. The study found that the mechanical impact of the sensitivity for IPMC sensor will be increase when the length of the sensor structure decrease. (Khmelnitskiy *et al.*, 2018).

As far as the IPMC size is concerned, it has been proved that the reducing of the IPMC strip length or increasing of the IPCM width will increase the amplitude of the sensing (Bonomo *et al.*, 2006). The test for this experiment was perform to a difference structure of the IPMC with a fix length and wide of the IPMC strip. In this research, the IPMC will be simulated by using COMSOL to determine the output voltage produced when the IPMC is bending

When the metal of the IPMC had a difference potential, the mobile cation movement toward the cathode led to the bending motion of the IPMC (toward a positive side of the voltage supply) as shown in a Figure 2. This principle is able to make the IPMC to act as an actuator. On others hand, the bending on the IPMC will produce the difference potential due to the pressure induced on the ionic structure (Pugal *et al.*, 2016). Hence, this difference potential making IPMC able to act as a sensor or energy harvester (Zhao *et al.*, 2018). The potential difference of the IPMC can be tested by performing a force load test as shown in Figure 3 (Bhandari, Lee and Ahn, 2012; Tiwari and Kim, 2012).

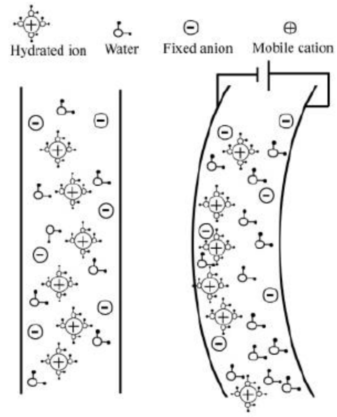

Figure 2: An illustration of a working principle of the IPMC (Bhandari, Lee and Ahn, 2012).

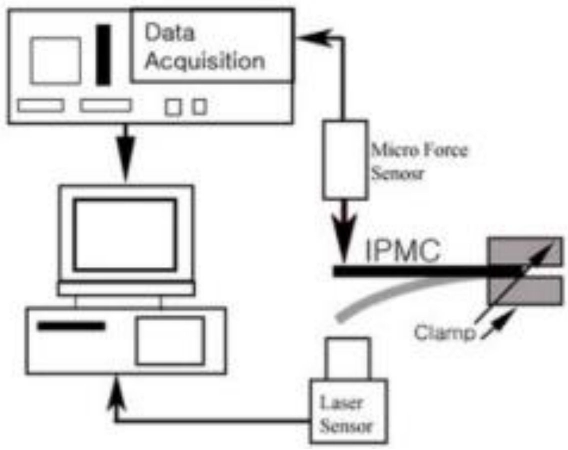

Figure 3: A setup for the sensor or energy harvesters

In general, the capable of IPMC to act as a sensor or actuator due to the induction of ionic current and resulting non-zero spatial charge in the metal. The Nernst-Plank equation can be used to calculate the ionic current in the polymer (Pugal *et al.*, 2016).

$$\frac{\partial C}{\partial t} + \nabla.(-D\nabla C - z\mu FC\nabla\phi - \mu C\Delta V\nabla P) = 0 \qquad (2.1)$$

Where

C = cation concentration

D = the diffusion coefficient

Vc = the molar volume which quantifies the cation hydrophilicity

Φ = electric potential in the polymer

μ = cation mobility

F = Faraday's constant

z = charge number

P = Solvent pressure

The mobility of the cation can be expressed as:

$$\mu = \frac{D}{RT} \tag{2.2}$$

Where

R = gas constant

T = absolute temperature

From the Nernst-Planck equation, three difference field gradients namely electric potential gradient $\nabla\phi$, concentration gradient ∇C, and solvent pressure gradient ∇P exist to change the magnitude of the IPMC. The concept of the IPMC as a sensor and actuator had shown in the Figure 4 (Pugal *et al.*, 2016). In sensor application, the potential gradient, $\nabla\phi$ had the opposite direction because the bending was induced by the pressure gradient ∇P. The potential ϕ can be described with Poisson's equation.

$$-\nabla^2\phi = \frac{\rho}{\varepsilon} \tag{2.3}$$

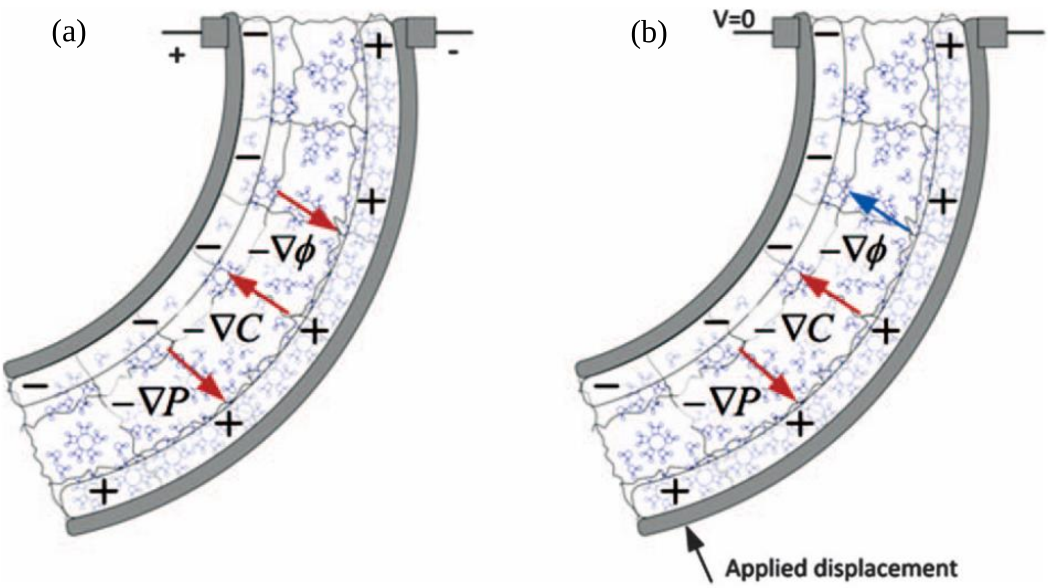

Figure 4: A concept of the IPMC as an actuator (a) or a sensor (b)

2.4 Application of the IPMC

Nafion as a main material used in the IPMC have been subject to a numerous investigations for their ionic properties and application in ionic-electric device (Hong, Almomani and Montazami, 2017). Among all of the ionic-electric device, IPMC have received less attention due to the inconsistent result of the experiment (Hong, Almomani and Montazami, 2017). However, high flexibility, easy processing, and a light weight of the IPMC properties initiate the future study as it was really useful in the robotic and biomedical application (Shahinpoor and J Kim, 2005).

2.4.1 Biomedical Applications

The large flexibility, softness, low power and biomimetic of the IPMC given advantages in the biomedical application (Pugal *et al.*, 2010). There was a lot of the application used in a medical application such as a heart compression device, surgical tools, peristaltic pumps, artificial muscles, drug delivery device and etc. (Shahinpoor *et al.*, 1998; Shahinpoor and J Kim, 2005; Chang, Chee and Lim, 2018).

The heart compression device was used as an artificial ventricular assist to a heart patient with a heart abnormalities. Figure 5 shows the setup of the heart compression and actual IPMCs design (Shahinpoor, 1992). Four IPMCs were used as a gripper to press the heart when the heart shows an abnormality. The voltage from the battery was applied into the IPMC when the abnormal signal of the heart detected. The flexible and softness of the IPMCs was a good material to press the heart as it can avoid any injury on the heart. The bending of the IPMCs will help the heart functionality as a backup force to support the blood circulation.

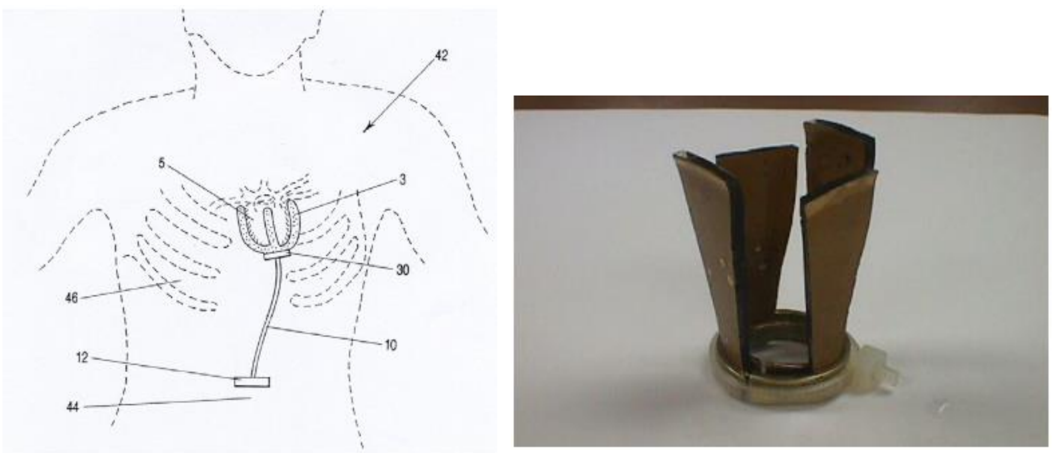

Figure 5: Setup and design of the heart compression using IPMC.

The surgical tools made from IPMCs were used for a diagnostics and intra-cavity endoscopic surgery. The small strip of IPMCs can help to navigate the small interval cavities in the body. Beside that, the tools also been used as a surgical scalpel to undertake small and precise cutting (Pugal *et al.*, 2010; Fu, McDaid and Aw, 2013; Khan *et al.*, 2018). The voltage was applied on the IPMCs structure to control the scalpel force as shown in Figure 6.

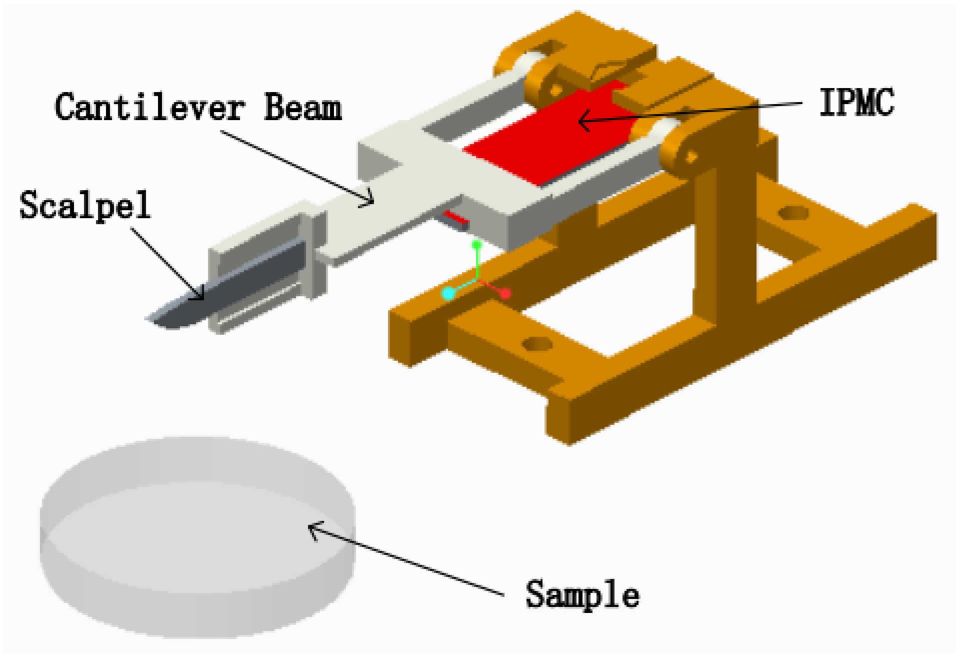

Figure 6: Surgical scalpel tool.

The artificial muscles were contructed by attaching several IPMCs as a segment and amploying a suitable voltage to control each of the segments (Kaneda *et al.*, 2003; Shahinpoor and J Kim, 2005; Jain *et al.*, 2010; Shahinpoor, 2015). Each IPMCs was connected to a voltage source to control the segment of each finger accordingly. Figure 7 shown a concept of the artificial finger which each of the finger was installed with the IPMCs.

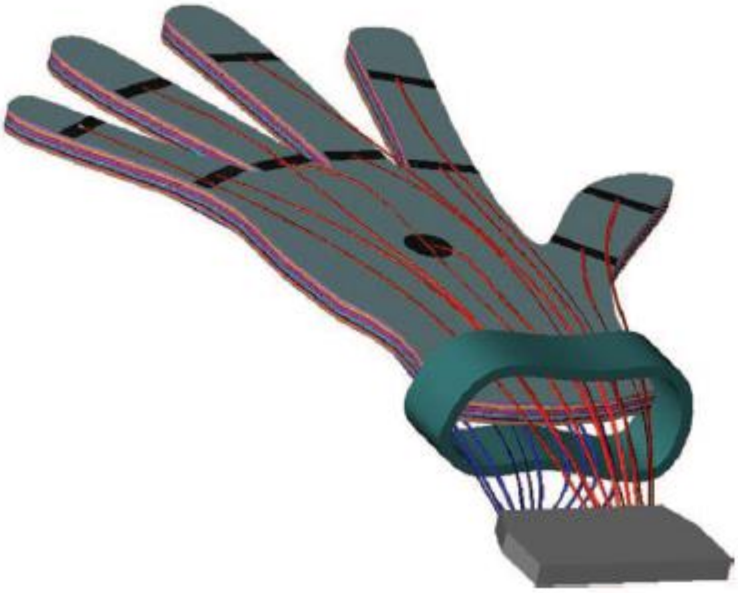

Figure 7: Drawing concept of the artificial fingers.

A drug deleviry device was used to release the drug inside the body when the device was delived at the target location. IPMCs was used in the device as a drug release as shown in Figure 8. The signal triggered into the device will activate the IPMCs by bending the tips. The low voltage input required to bend the IPMCs tip was very importance for the drug delivery to avoid any damage on human body (Shahinpoor, 2015; Chang, Chee and Lim, 2018; Liang Chang *et al.*, 2019). The low signal such as radio-frequency was able to unseal the device inside the human body.

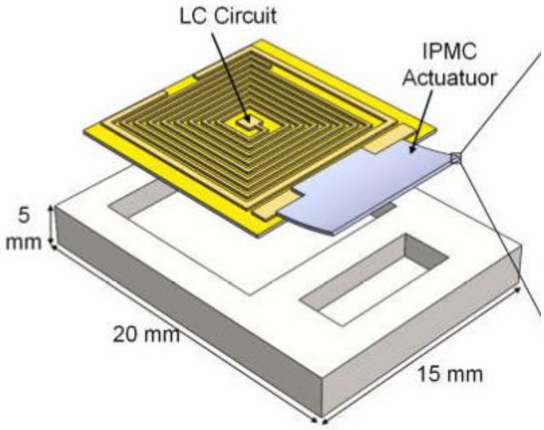

Figure 8: A concept of a micro-reservoir based drug delivery device.

2.4.2 Industrial Applications

In industry application, IPMC was very useful to use as an actuator and a sensor. The example of the application been use in industry are a gripper, three dimensional actuator, robotic swimmer, micro-pump, probes, robot arm and etc.

By supplying a voltage into three difference IPMCs, the IPMC will bend and react as an actuator. The proper design of the IPMC structure able to bend the IPMC and it make it act as a gripper. Figure 9 shown a gripper structure and application in the industry (Bhat and Kim, 2003; Pugal *et al.*, 2010; Khan *et al.*, 2017) .

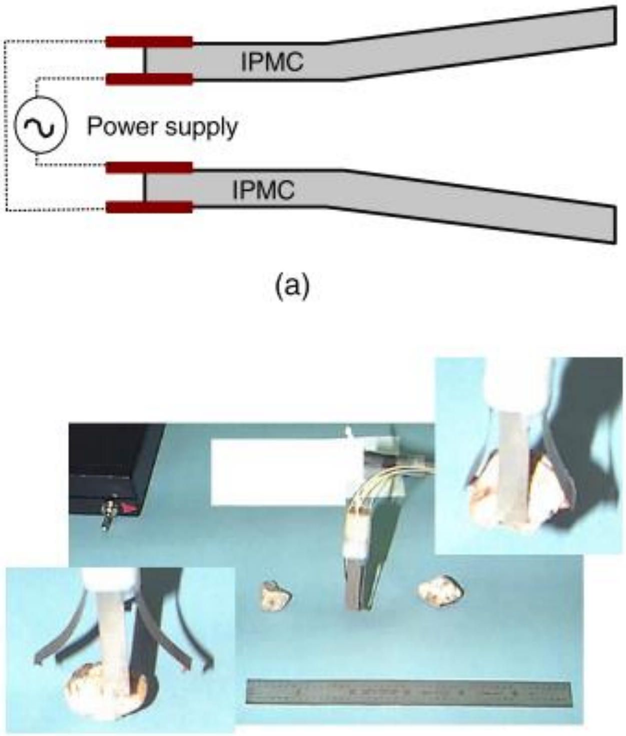

Figure 9: The gripper used in the industry application.

Figure 10 shows a schematic diagram of the three dimensional actuator in a shape of cylindrical (Kim and Shahinpoor, 2001; Shahinpoor and Kim, 2002; Palmre *et al.*, 2013). The structure consist of four sector of IPMCs which was combined to form a cylindrical shape. Each of the IPMCs sectored were connected with the input signal as a supply source to move the structure. The structure was capable to move in circular which are useful to in the artificial muscles.

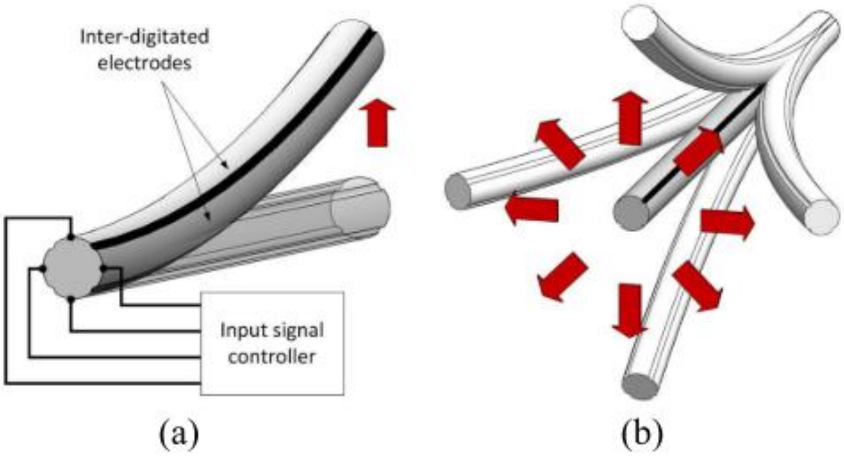

Figure 10: Schematic diagram of the cylindrical IPMCs with 4 sectored electrode (a) an illustration structure (b) a movement of IPMCs.

A robotics swimmer were another application of the IPMCs in the industry as shown in Figure 11. The fin was attached with a IPMCs strip to control the direction of the robotic fish (Shahinpoor, 1992; Shahinpoor and J Kim, 2005; Chen, Hou and Ye, 2018). The bending of the IPMCs will change the position of the fin either on the left direction or on the right direction (Chen, Um and Bart-Smith, 2012).

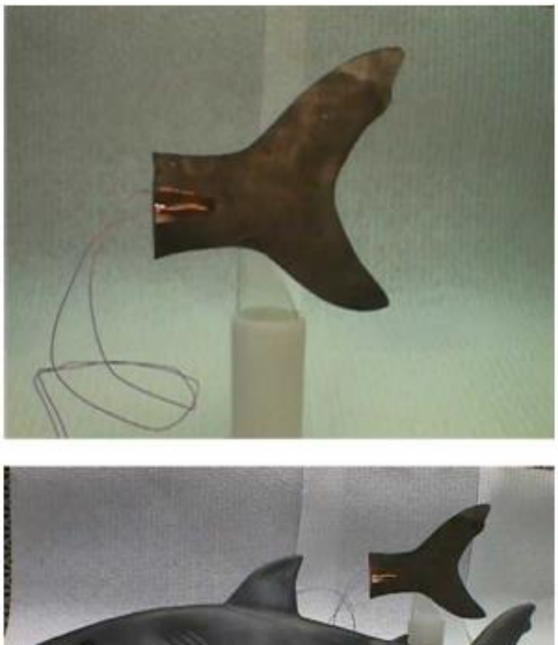

Figure 11: Robotic fish equipped with IPMCs.

IPMCs also been use in the micro-pump application due to the low driven voltage, self-sensing ability and flexiable operation (Nam and Ahn, 2012). The square of the IPMCs was cutted in a cross direction to make an opening on the IPMCs structure as shown in Figure 12. Once the voltage source was applied, the centre of IPMCs structure will bent and return to origal position once the source was cut-off. The repeated movement of the IPMCs will produced a difference pressure between inner and outter layer of IPMCs. With a proper design structure, the difference pressure between a layer were able to function as a micro-pump (Wang and Fu, 2018; Yanjie *et al.*, 2018).

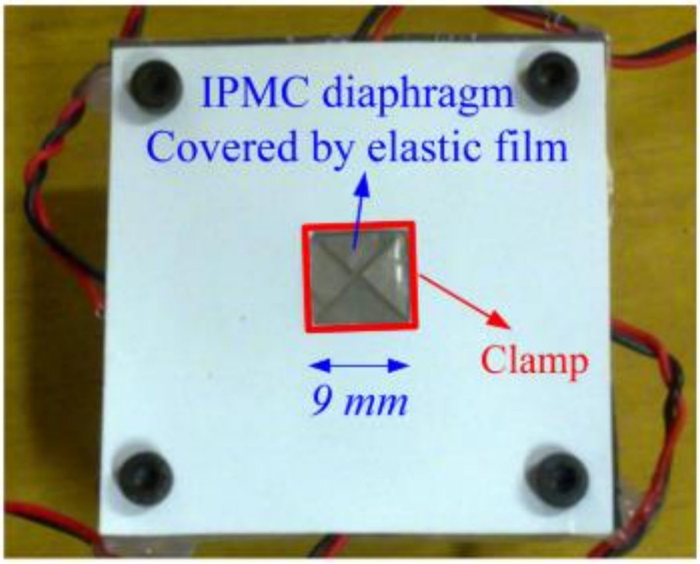

Figure 12: Design of the IPMCs micro-pump.

2.5 Summary

Basically, the ability of IPMC to act as a sensor or actuator was really helpful in the worldwide application. As an actuator, IPMC able to bend at the large amount of deformation when there are electric potential applied. The bending of the IPMC will produce the difference potential which make the IPMC to act as a sensor. However, stability and controllability of the IPMC was still difficult as the solvent content in IPMC can be loss when operate more than 1.23V or degraded by a time (Bhandari, Lee and Ahn, 2012).

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter will cover the work plan of the simulation from the designing the IPMC sensor until the display the result of the simulation. The simulation was completed by using the COMSOL Multiphysics and the IPMC design was simulated by using 2D space dimension. The parameter and properties of the IPMC was collected based on the previous study listed in the reference. A rectangular 2D IPMC was modelling to simulate the electrical output of the IPMC when the load was apply on the IPMC tip.

3.2 Flowchart of the Study

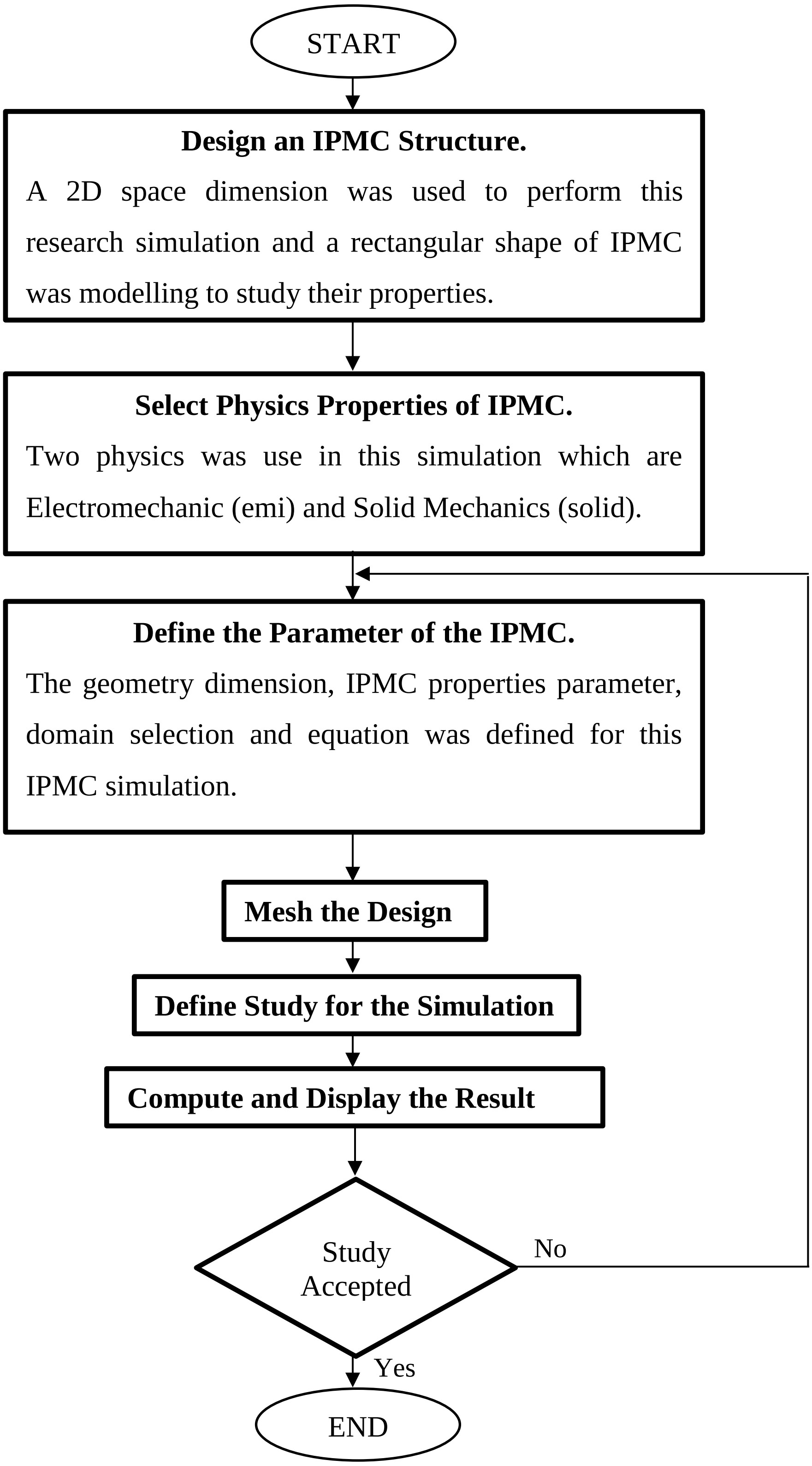

Chart 1: Flowchart of the IPMC Simulation

3.3 Structure of the IPMC

For a first step of the simulation, the design of the IPMC structure was created using COMSOL Multiphysics.

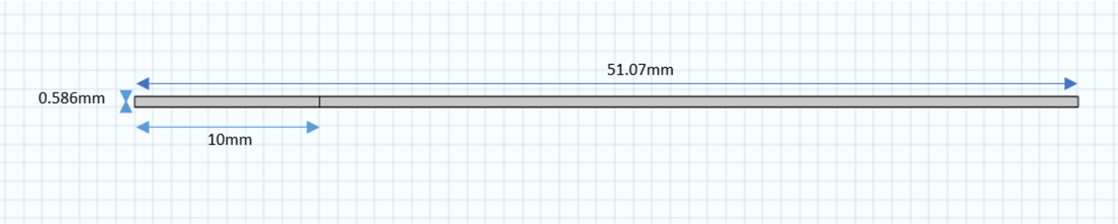

Figure 13: Overview of the IPMC structure

Figure 13 shows the overview of the IPMC used in this simulation. The total size of the IPMC is 51.07mm X 0.586mm X 9.94mm (Width X Height X Depth). The depth of the structure was defined in the global parameter as the simulation is done in 2D space dimension. On the overall width of this IPMC, 10mm from the left of the dimension was use as a clamp to the IPMC. The purpose of this clamp is to hold the IPMC when the load was apply on the tip.

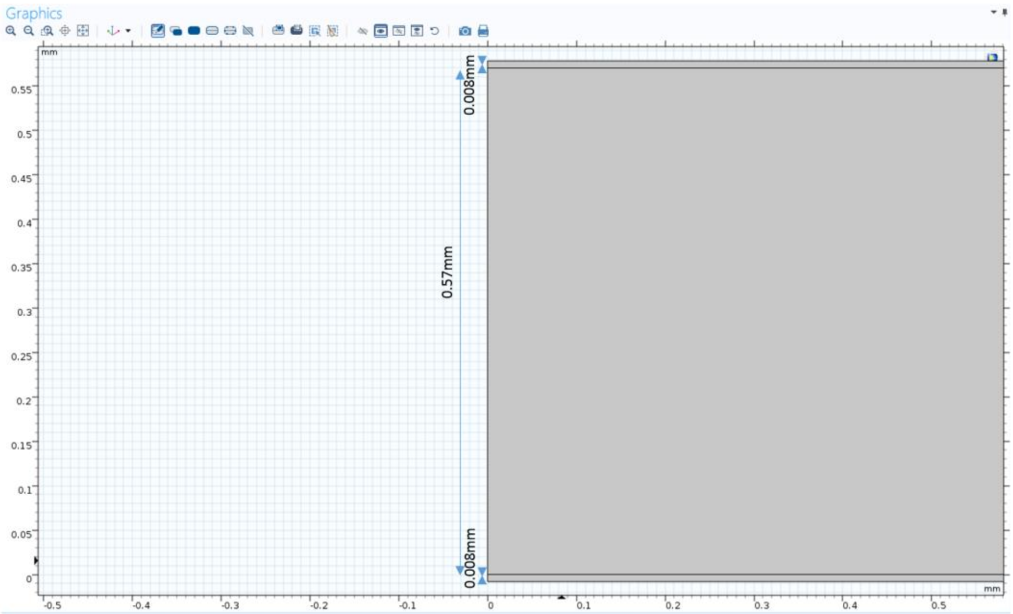

Figure 14: The Zooming view of IPMC structure

Figure 14 shows the 3 layers of the IPMC used in this study. The upper and lower layer with a thickness of 0.008mm are metal that have been plated on the polymer with a thickness of 0.57mm. The thickness structure of the metal and polymer was maintain until the tip of the IPMC. In summary, the geometry contents fours rectangular (IPMC structure and clamper) and two points (use to fix the clamper structure) as shown in Figure 15.

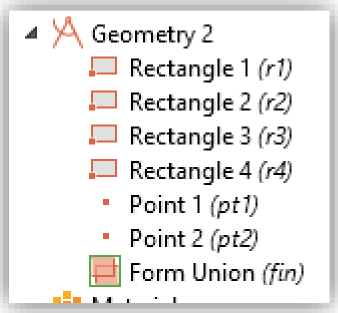

Figure 15: List of geometry

The simulation was repeat with the difference dimension of IPMCs. For the first study parameter, five difference lengths of IPMCs which are 20.07mm, 30.07mm, 40.07mm, 50.07mm and 60.07 mm was design with the same thickness of the IPMCs. For the second study parameter, three difference heights of the IPMCs was design with the constant length of 51.07mm. The thickness of 0.296mm, 0.586mm and 1.016mm was use to study the effect of the thickness with a IPMCs output voltage. Figure 16 shows IPMCs with a thickness of 0.296mm and Figure 17 shows IPMCs with a thickness of 1.016mm.

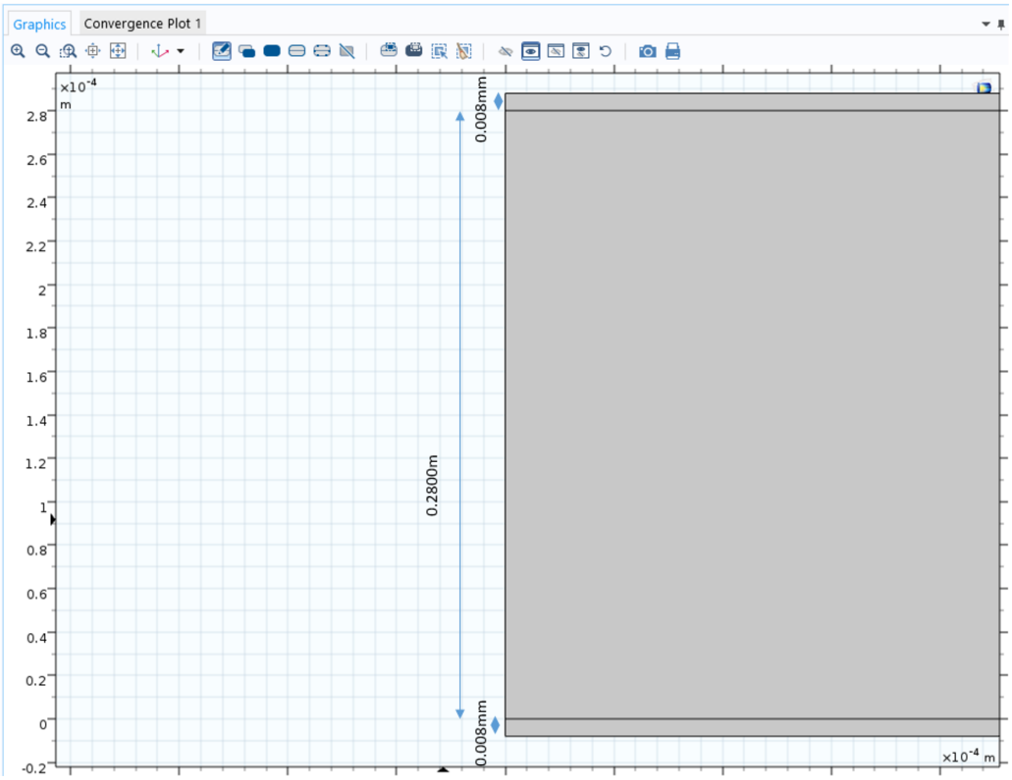

Figure 16: The Zooming view of IPMC structure with thickness of 0.296mm.

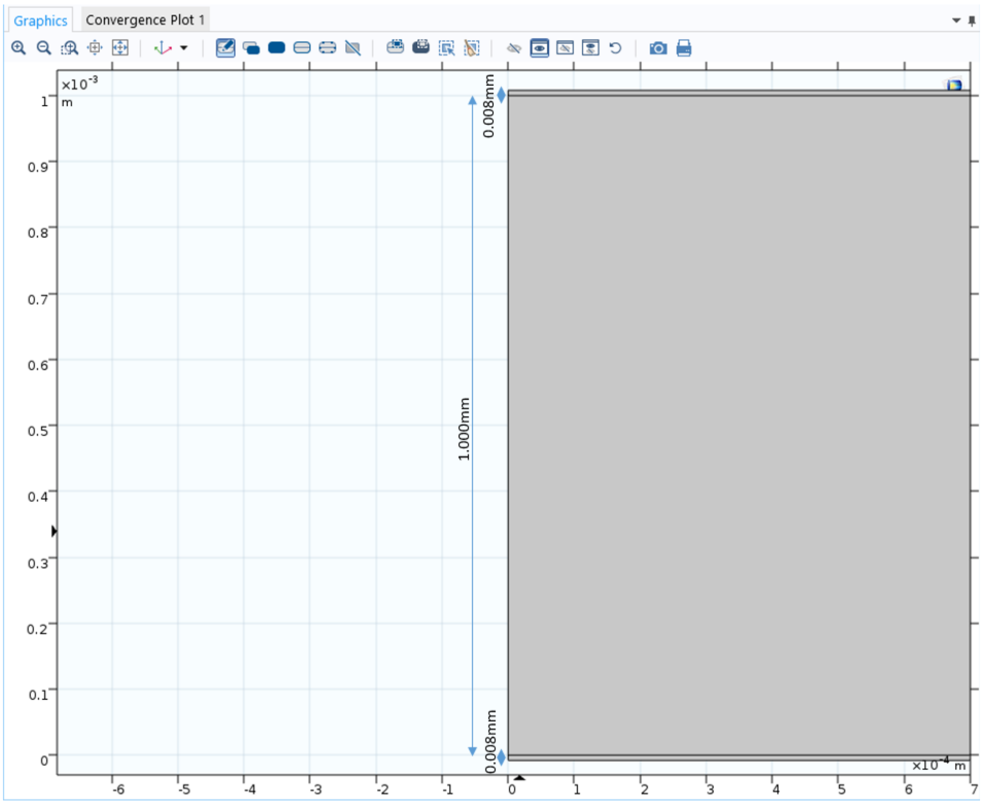

Figure 17: The Zooming view of IPMC structure with thickness of 1.016mm.

3.4 Physics properties of the IPMC

Secondly, two physics modules were applied in this simulation which are the solid mechanics (solid), and the electro-mechanics (emi). Figure 19 shows the list of the physics module apply on this simulation. In a solid physics module, 1kPa load was apply on top of the IPMC and was repeated on bottom of the IPMC by using boundary load. The clamper boundary was selected as a fixed constrain to hold the IPMC when the load is applied. Terminal 1 and Terminal 2 was used to measure the voltage of the noble plate as shown in Figure 18.

Figure 18: Terminal of the electric potential

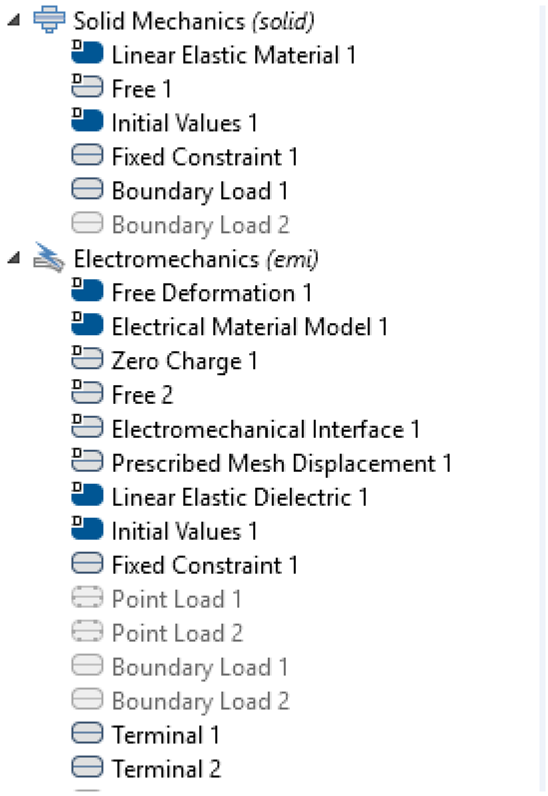

Figure 19: Physics module of the simulation

3.5 Parameter of the IPMC

The parameter of the IPMC was declare by refer to the published journal (Pugal *et al.*, 2016) as a material properties for this simulation. Table 1 shows the list of the parameter used in this simulation.

Table 1: Constant parameters of IPMC properties

Parameter Name	Name	Expression
Depth of IPMC	Width_IPMC	9.94 [mm]
Polymer Young modulus	Young_IPMC	41 [MPa]
Polymer Poisson constant	Poisson_IPMC	0.49
Polymer Density constant	Density_IPMC	2000 [kg/m^3]

3.6 Mesh the Design

For the next step of the simulation, the structure of the IPMC required to be meshing to carry out the analysis study. For this simulation, the left edge of the structure was meshed using a mesh type and distributed. The remaining of the domain was meshed using a mapped type as shown in Figure 20.

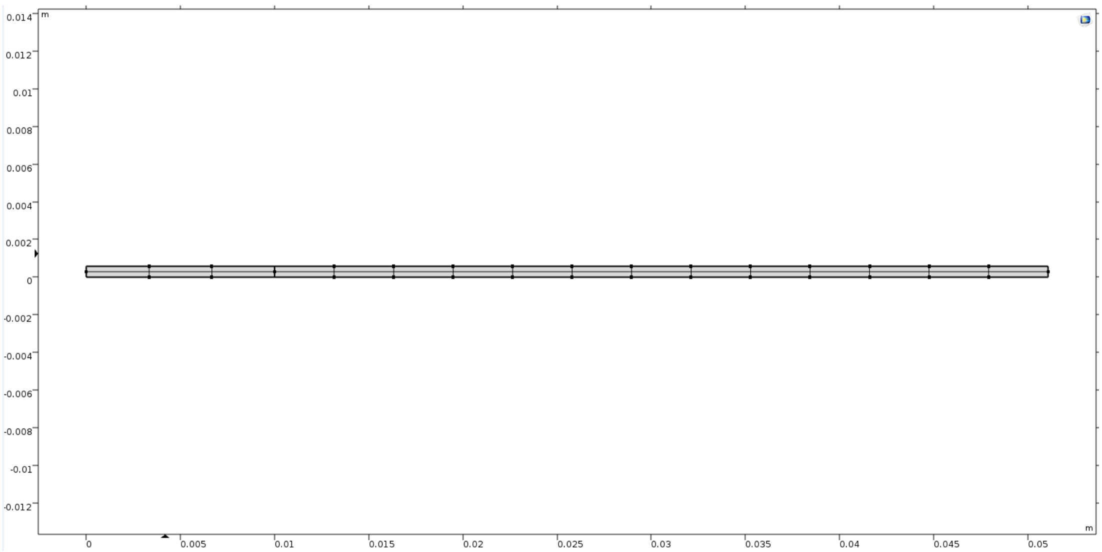

Figure 20: Mesh structure of the IPMC

3.7 Define Study for the Simulation

Stationary present study was used to simulate the IPMC properties based on the displacement and electric potential.

3.8 Compute and Display a Result

Lastly, the study of the designed IPMC was compute to display the surface structure of the IPMC when load applied. A 1D plot also been used to display the graph of the voltage and displacement versus load applied.

3.9 Summary

The simulation of the IPMC to act as a sensor was completed with the step as shown in the Chart 1. The step start from designing the structure of the IPMC until compute the study of the IPMC.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the result and explanation of the simulation which cover the von Mises stress when the load is applied on the IPMCs tip, electric potential between upper and lower metal and the relationship between the displacements of the IPMCs tip with a voltage difference. All of the result was collected using the COMSOL Multiphysics with the setup design as chapter 3.

4.2 Direction of Deflection Result of the IPMCs as a Sensor

Based on the design parameter listed in Chapter 3, the load was apply by a force per unit area and the shape of the IPMCs was created in the 2D space dimension. Figure 21 shown the structure of the IPMCs with no load is applied, Figure 22 shown the structure of the IPMCs with a positive load is applied at 0.5kPa and Figure 23 shown the structure of the IPMCs with a negative load is applied at 0.5kPa respectively.

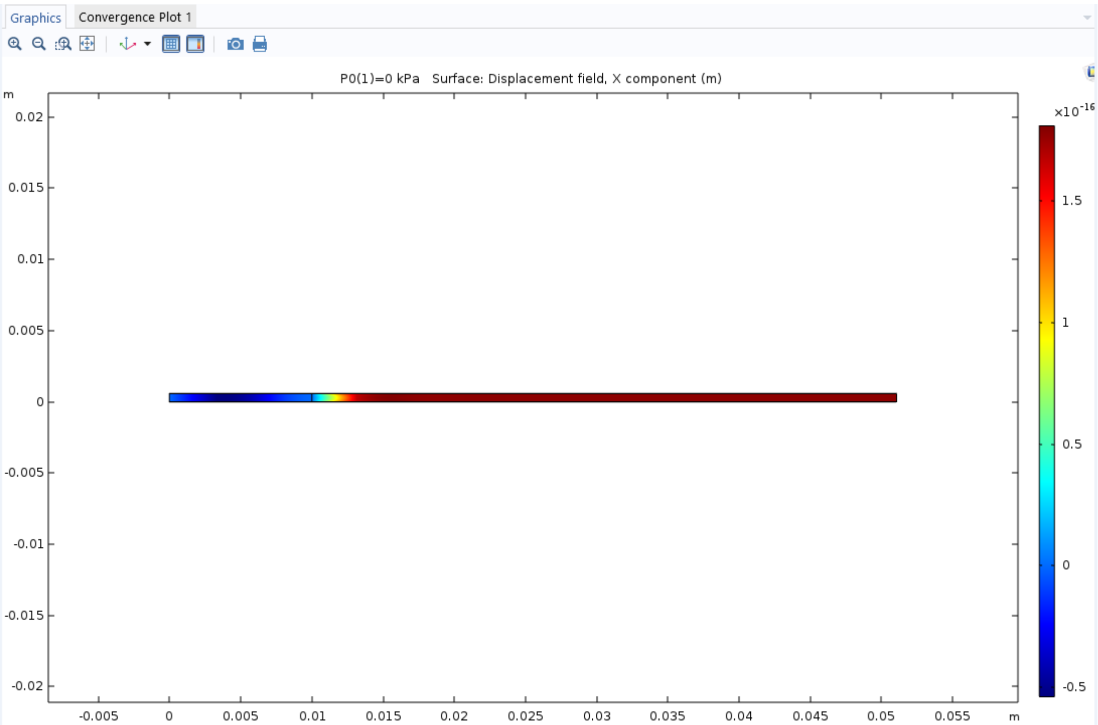

Figure 21: The IPMC structure when no load is applied.

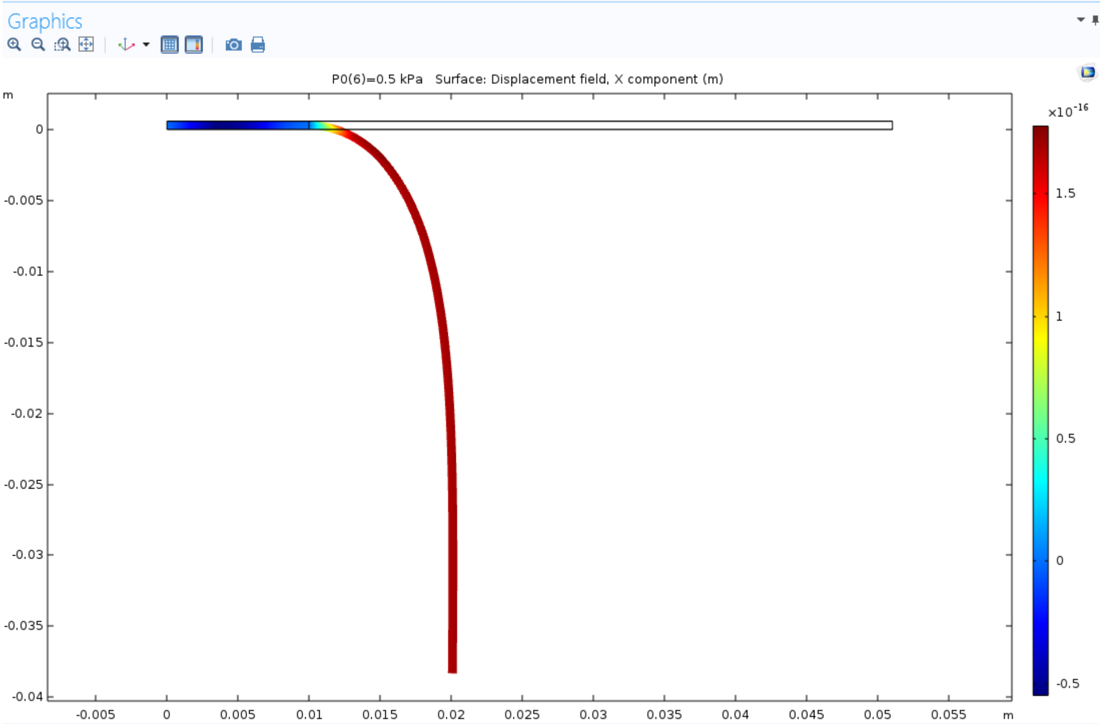

Figure 22: The IPMC structure when positive load is applied.

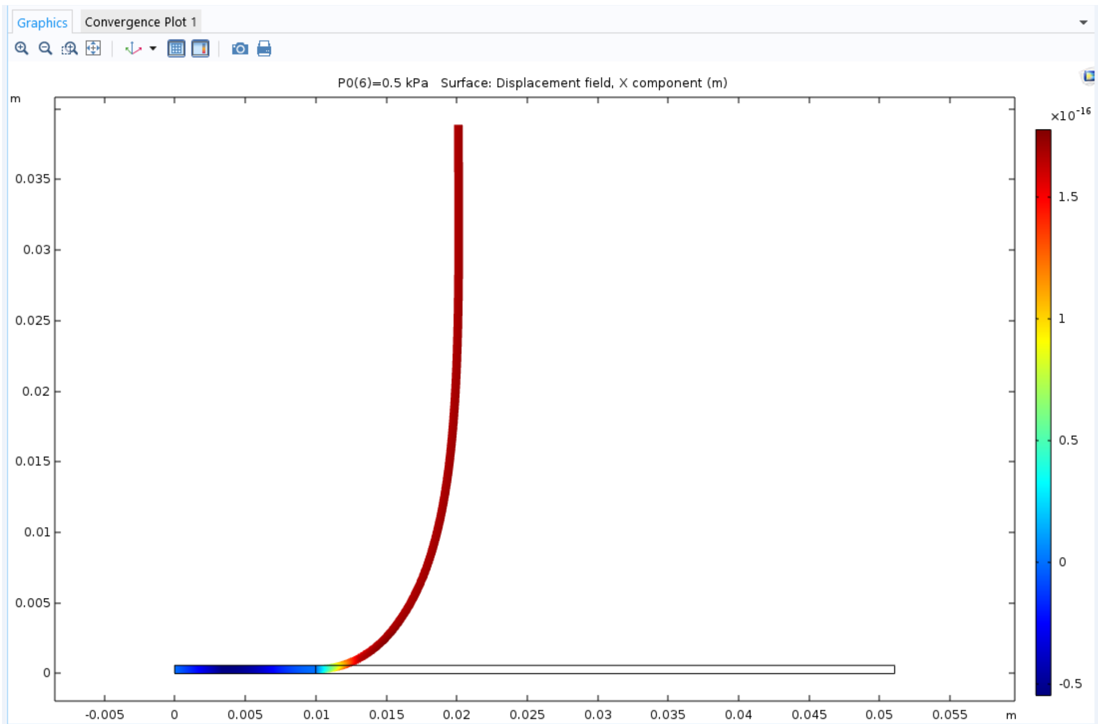

Figure 23: The IPMC structure when negative load is applied.

From this simulation, the structure of the IPMCs was response with the direction of the load applied. The IPMCs tip was move upward when the negative load was applied and move downward when the negative load was applied. The tip also static when no load was applied as shown in figure 15. In addition, IPMCs was bending for almost 90º from the original position when 0.5kPa load was applied as shown in Figure 22 and Figure 23.

4.3 Bending Result of the IPMCs as a Sensor

The degree of the IPMCs tips bending was depends from the load applied on the tips. Figure 24 until Figure 34 shows a structure of the IPMCs with a difference load been applied on the top of the IPMCs structure. The difference load from zero until 1kPa was displayed with an increment of 0.1kPa.

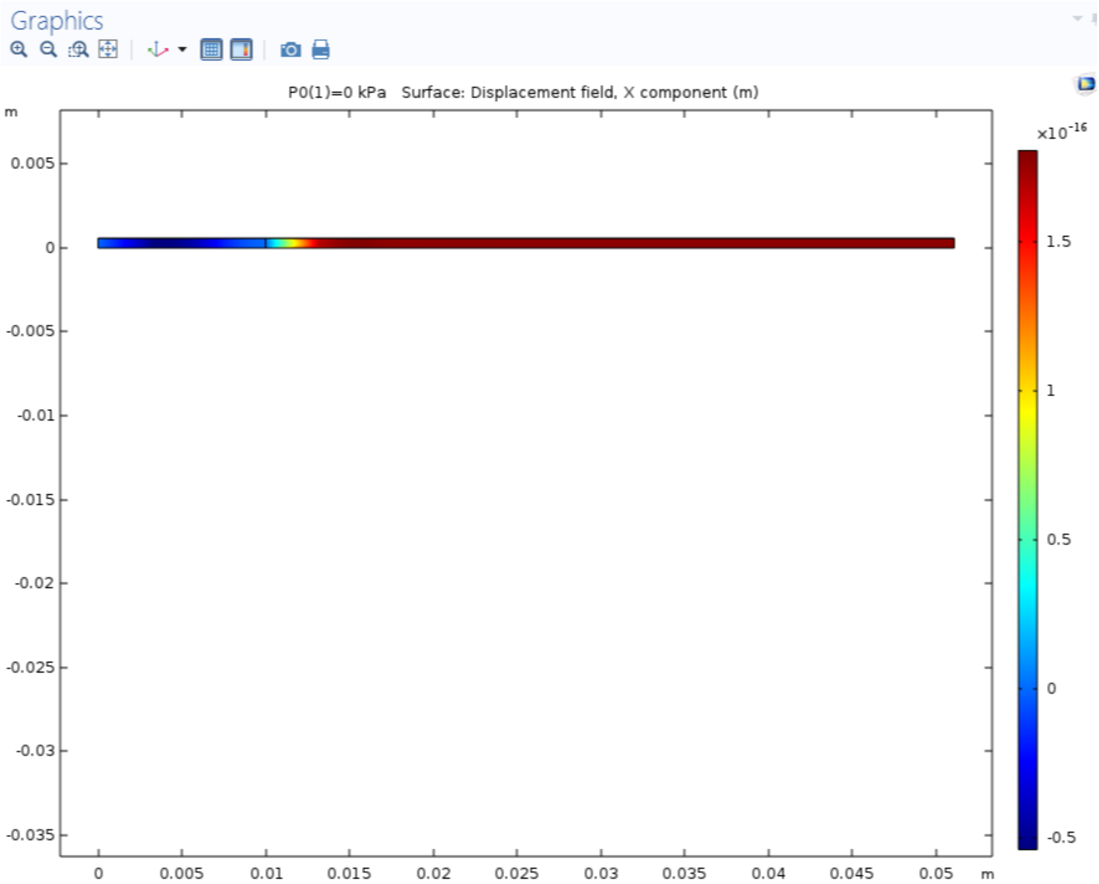

Figure 24: Bending of the IPMCs with a load of 0kPa.

From the Figure 24, the structure of the IPMCs was static. There are no movement on the structure of the IPMCs as there a no load being applied. So, all the displacement of the IPMCs was zero.

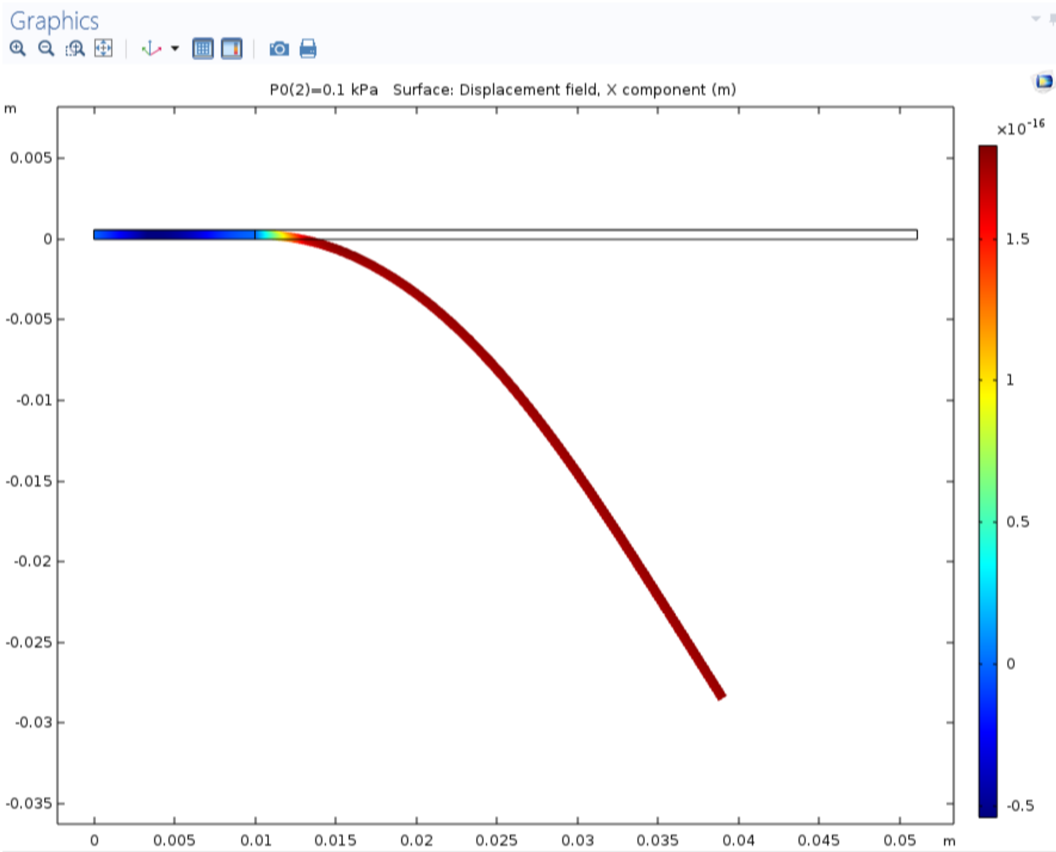

Figure 25: Bending of the IPMCs with a load of 0.1kPa.

From the Figure 25, 0.1kPa load was applied on top of the IPMCs resulting a bending of the IPMCs tip. The tips was bending around 15º of the original position with a displacement value of -0.03m. The bending of the 0.1kPa simulation produced an output of 7mV as shown in the Figure 39. The structure of the IPMCs only bent at the tips as the clamp was applied on the 10mm of the left IPMCs structure.

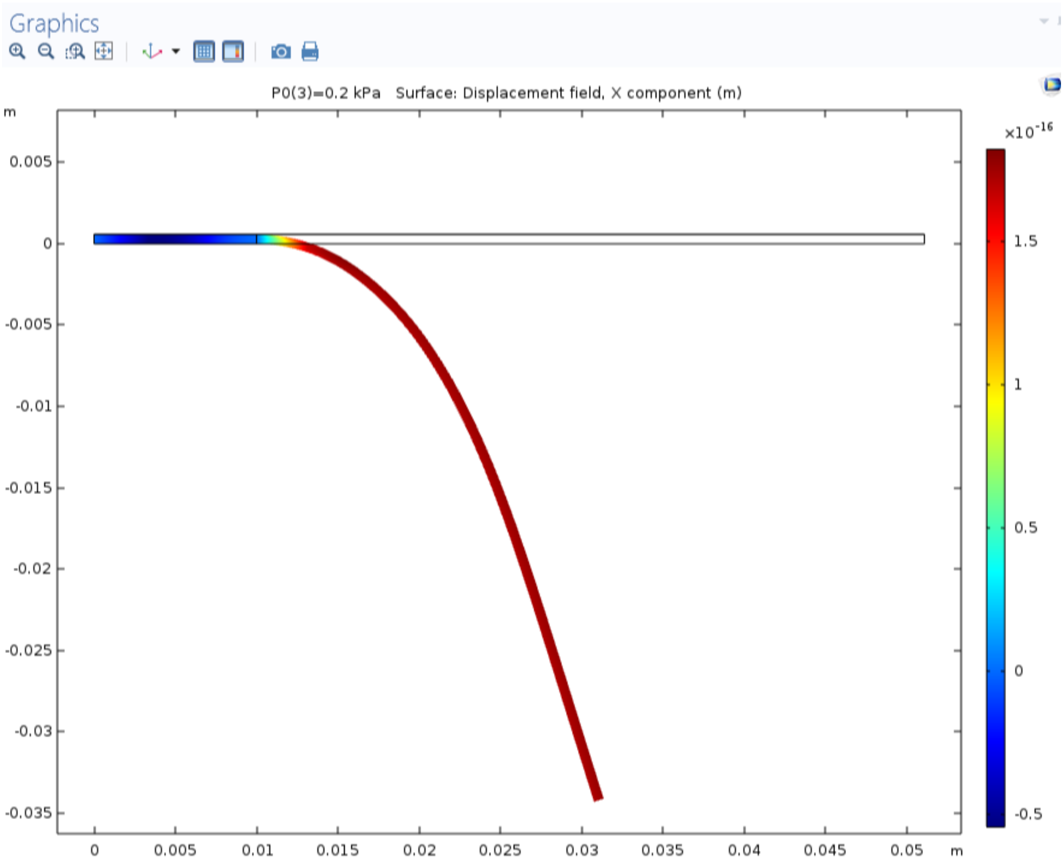

Figure 26: Bending of the IPMCs with a load of 0.2kPa.

Figure 26 shown a structure of the IPMCs with the load of 0.2kPa being applied on top of the IPMCS structure. The displacement of the structure was increased into -0.035m compare to the IPMCs structure when the load of 0.1kPa being applied. The tips was bending around 60º of the original position. This load simulation was produced an output of 11mV as shown in Figure 39.

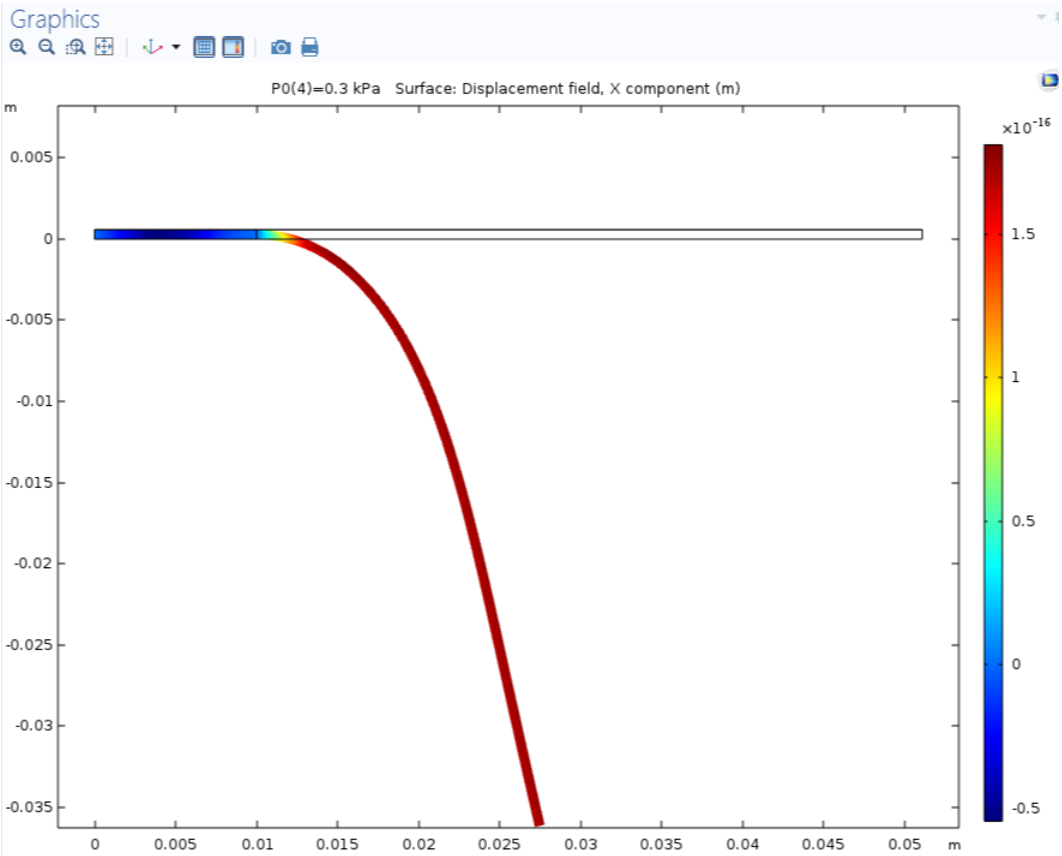

Figure 27: Bending of the IPMCs with a load of 0.3kPa.

Figure 27 shows the structure of the IPMCs when 0.3kPa load being applied. IPMCs tips bending was increasing compare to the load of 0.1kPa and 0.2kPa. The tips was bending around 70^{o} of the original position. This load simulation was produced an output of 15mV as shown in Figure 39. The displacement of the tips was also increased into more than -0.035m.

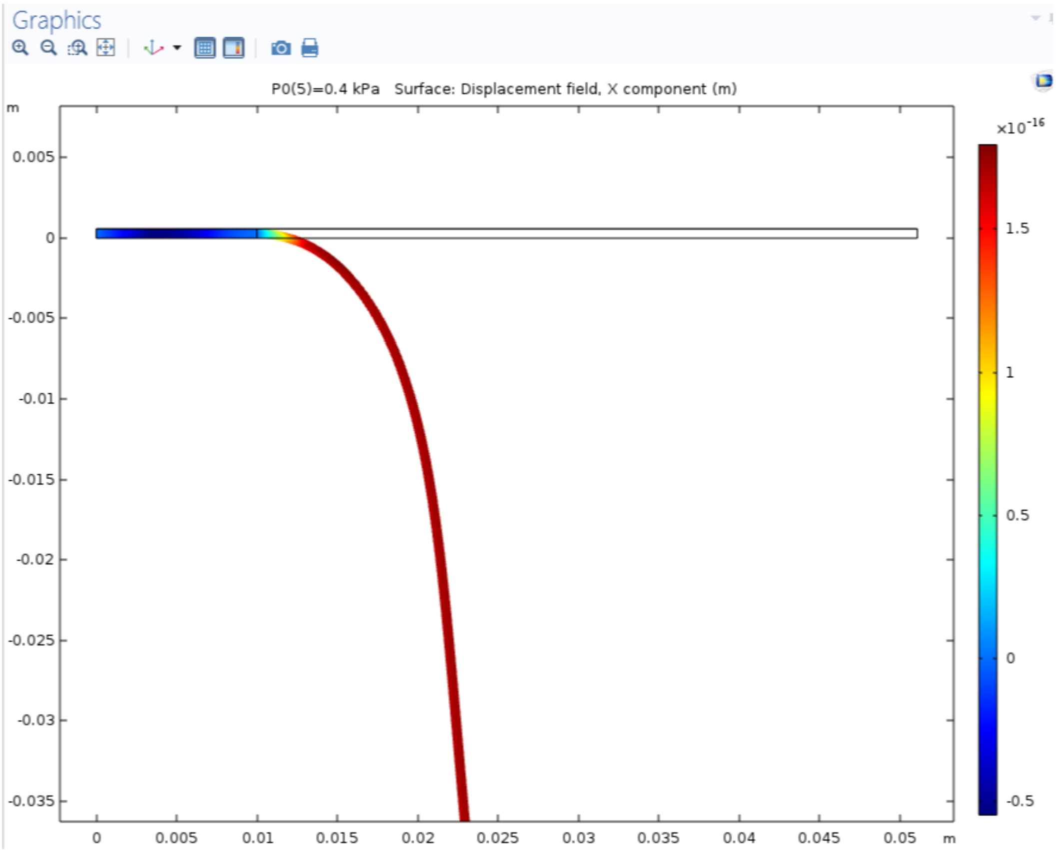

Figure 28: Bending of the IPMCs with a load of 0.4kPa.

Figure 28 shows the structure of the IPMCs when 0.4kPa load being applied. IPMCs tips bending was increasing compare to the previous simulation. The displacement of the tips was also increased into more than -0.035m. The tips was bending around 85^{o} of the original position. This load simulation was produced an output of 19mV as shown in Figure 39.

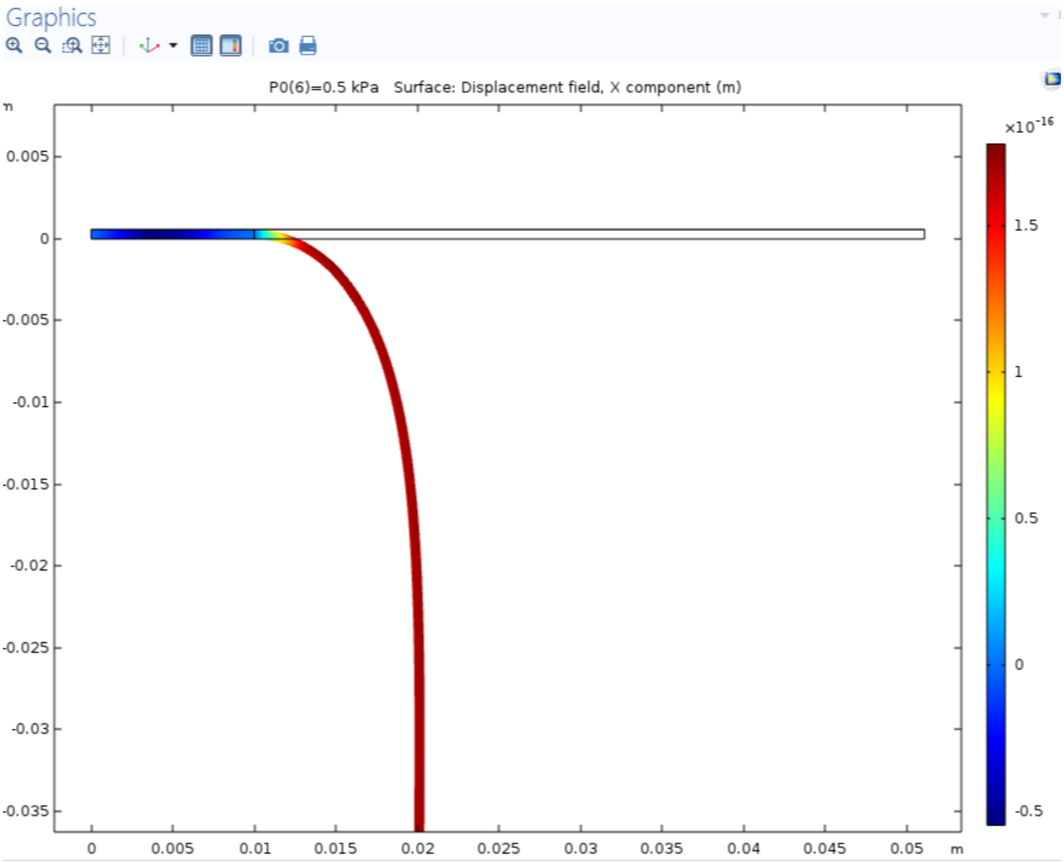

Figure 29: Bending of the IPMCs with a load of 0.5kPa.

Figure 29 shows the structure of the IPMCs when 0.5kPa load being applied. IPMCs tips bending was increasing compare to the previous simulation with the bending around 90º of the original position. The displacement of the tips was also increased into more than -0.035m. This load simulation was produced an output of 22.5mV as shown in Figure 39.

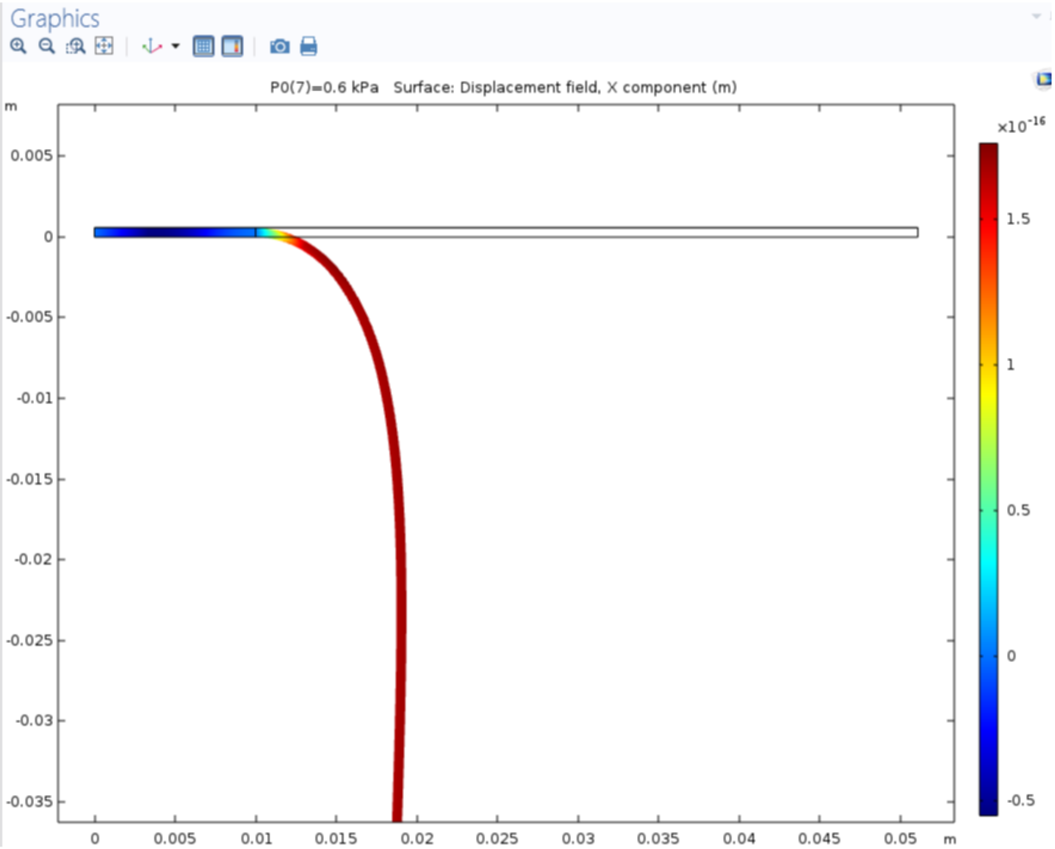

Figure 30: Bending of the IPMCs with a load of 0.6kPa.

Figure 30 shows the structure of the IPMCs when 0.6kPa load being applied. IPMCs tips bending was increasing slightly compare to structure of the IPMCs with a load of 0.5kPa. There was no change on the displacement of the tips as it already reach the maximum displacement. This load simulation was produced an output of 25.5mV as shown in Figure 39.

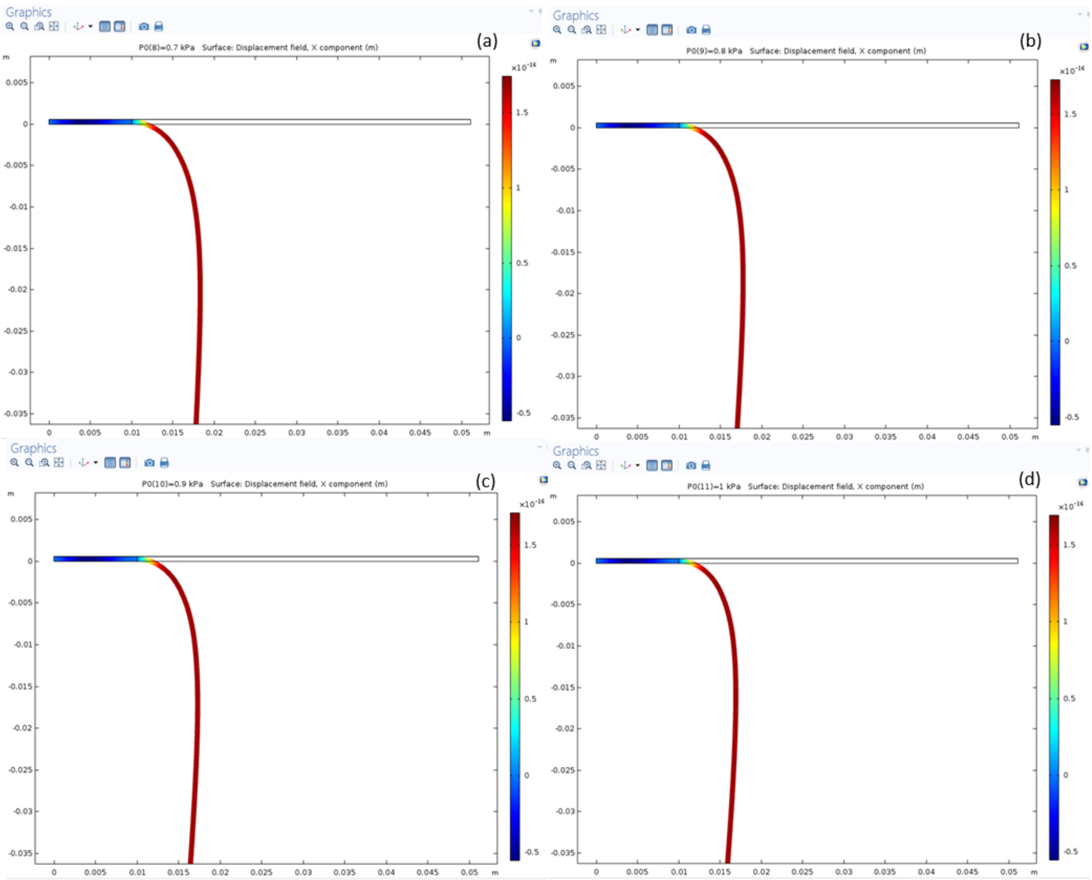

Figure 31: Bending of the IPMCs with a load of (a) 0.7kPa, (b) 0.8kPa, (c) 0.9kPa and (d) 1.0kPa.

Figure 31 shows the structure of the IPMCs when the load of 0.7kPa, 0.8kPa, 0.9kPa and 1.0kPa being applied. There was a slightly change of the IPMCs tips compare to structure of the IPMCs with a load of 0.6kPa. The displacement of the tips also reached the maximum value. The output of the simulation from 0.7kPa, 0.8kPa, 0.9kPa and 1.0kPa load were produced an output of 29mV, 32mV, 35mV and 38mV respectively. The result were shown in Figure 39.

From this simulation, the bending degree of the IPMCs were increase as the load being applied increased. However, the bending degree of the IPMCs at 0.5kPa load until 1.0kPa load only got a slightly change. The slightly change of bending degree was cause by the stress at the IPMC clamp which cause the high density at the bending angle.

4.4 Electrical potential of the IPMC as a Sensor

The surface plot on the electrical potential of the IPMC doesn't shown a large change when the IPMC is bending. This can be seen on both Figure 36 and Figure 37. However, terminal of the IPMC still have a small difference potential as shown in the Figure 38 and Figure 39.

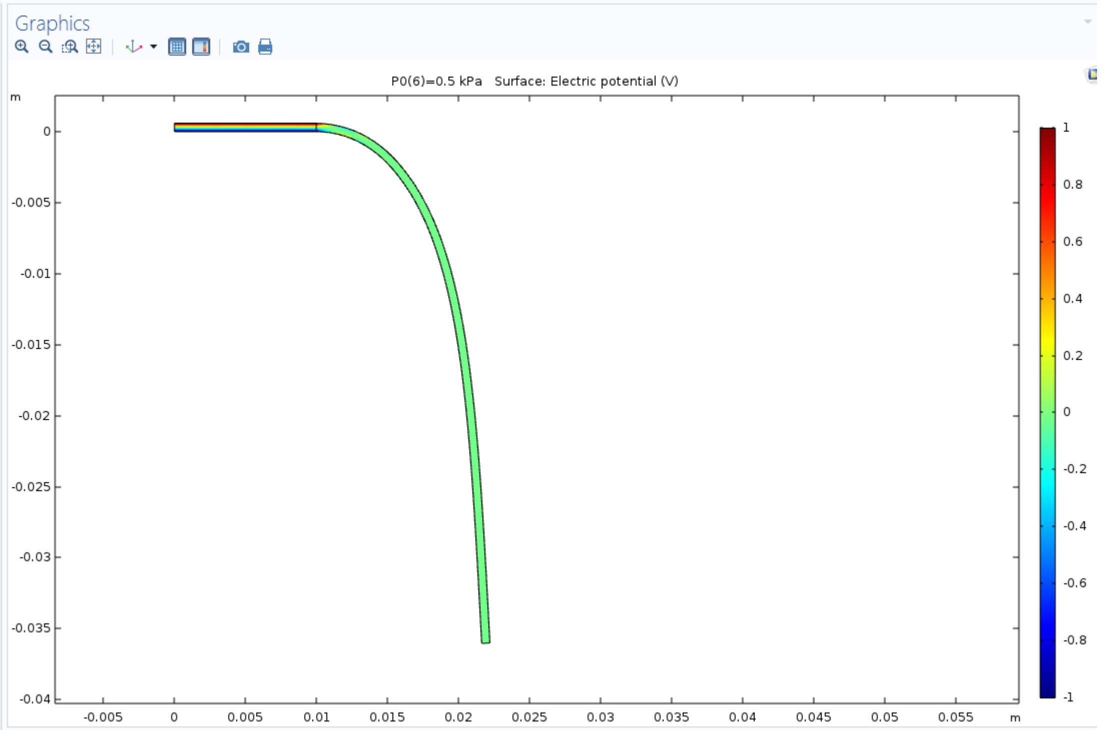

Figure 32: The electric potential stress when positive load is applied.

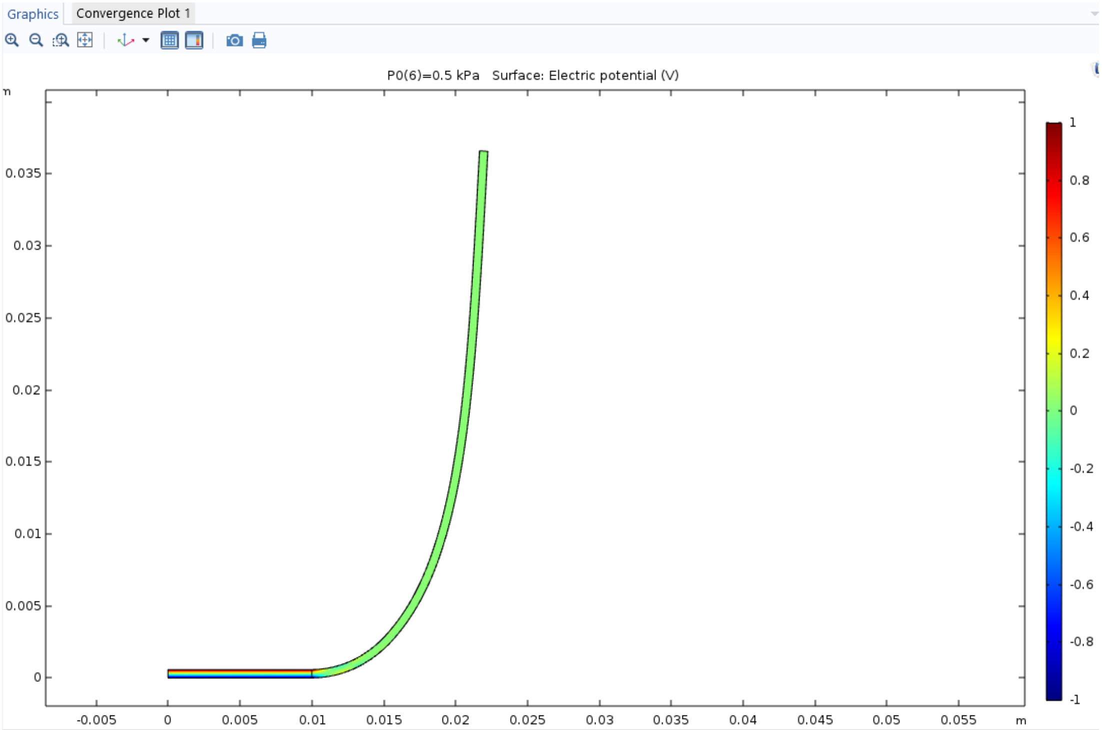

Figure 33: The electric potential stress when negative load is applied.

4.5 Relationship of Voltage and Tips Displacement Simulation

Figure 38 and Figure 39 shown an opposite pattern of the electric potential versus load applied. The result of both graph were matched with a theory as described in the Chapter 2. Besides that, we also can see that, IPMC only produce a small voltage difference when the load is applied. The maximum output voltage produced by the IPMC is only around 4mV and the minimum output around -4mV. From this simulation, the output voltage was increase as the load applied on IPMCs tip increased. The increasing of the output voltage was happened due to the bending of the IPMCs which cause more pressure induces on the ionic structure.

The displacement versus load graph in Figure 40 and Figure 41 shown that, both negative and positive load gave a same displacement of the IPMCs bending. In theory, the result was accepted because the noble metal in the IPMCs structure have a same thickness. On other hand, the displacement of the tips become more saturate when the load is applied from 0.5kPa until 1.0kPa. The larger bending of the IPMCs will increase the stress on the IPMCs clamp which limit the bending of the IPMCs. This will cause the IPMCs structure to reach it saturated position.

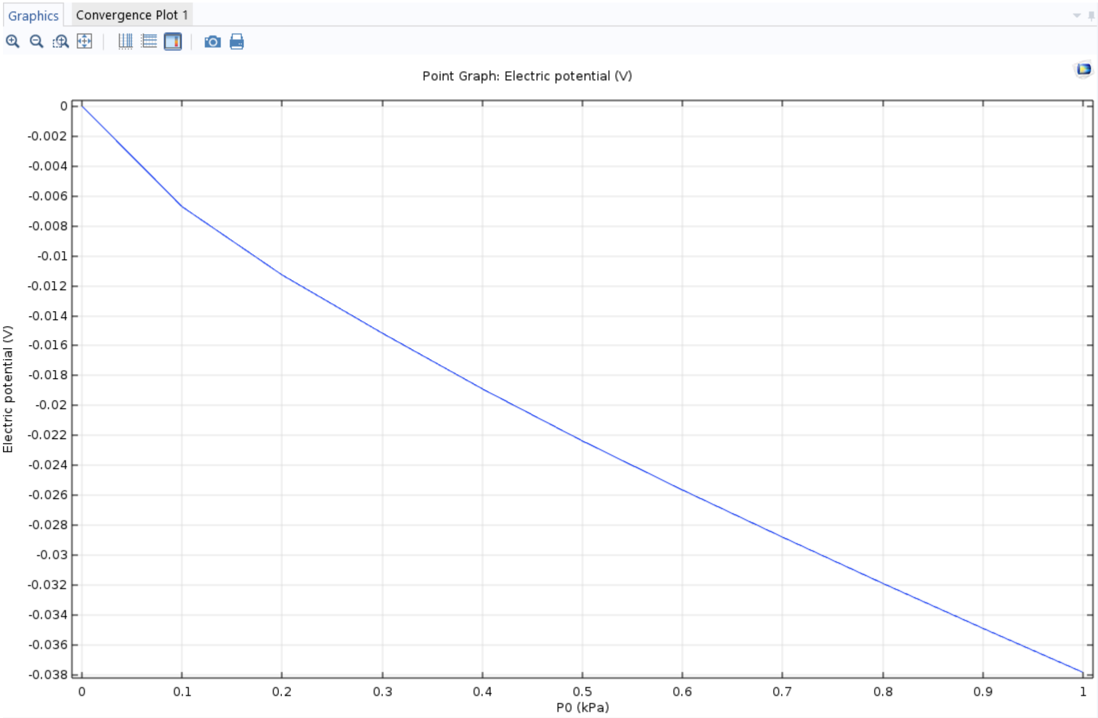

Figure 34: Electric potential versus load when positive load is applied.

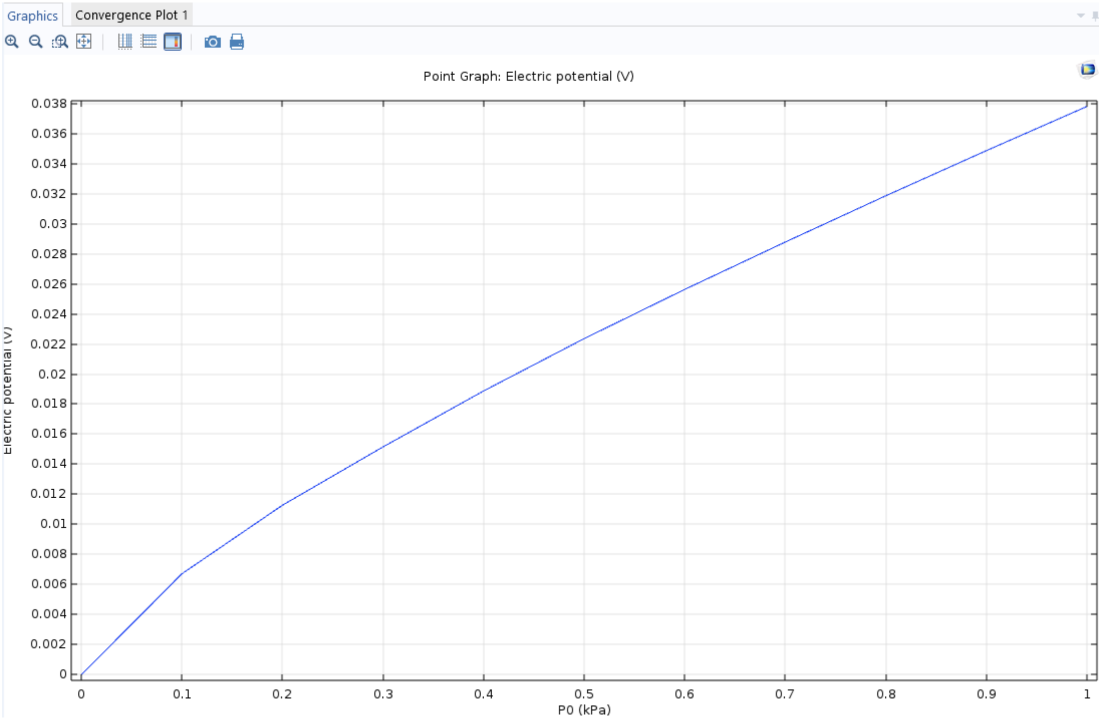

Figure 35: Electric potential versus load when negative load is applied.

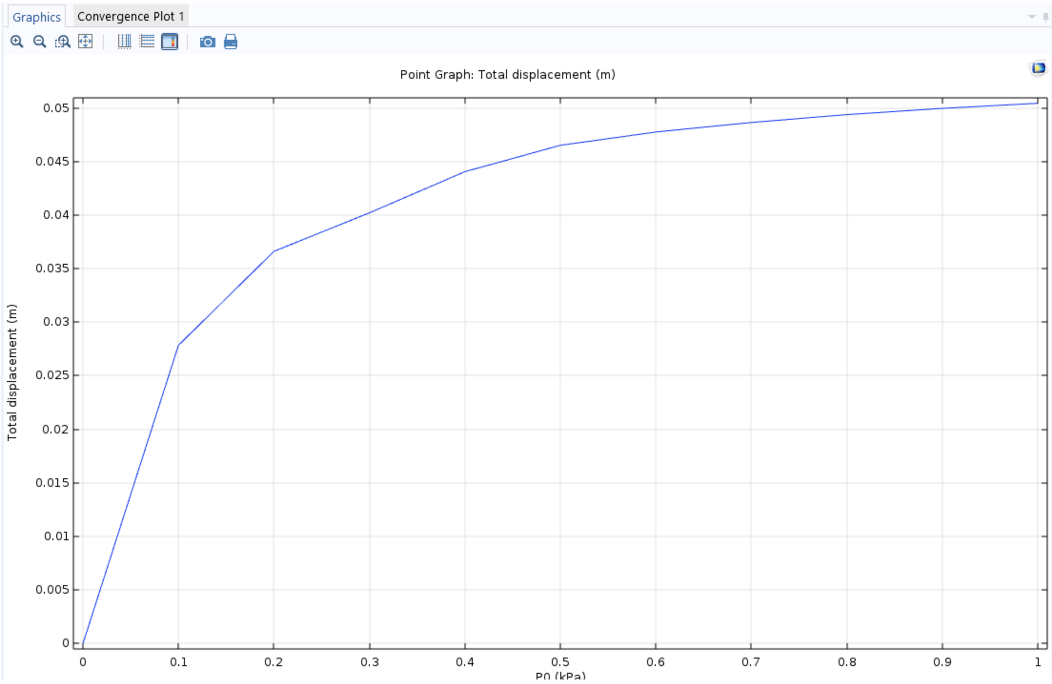

Figure 36: Displacement versus load when positive load is applied.

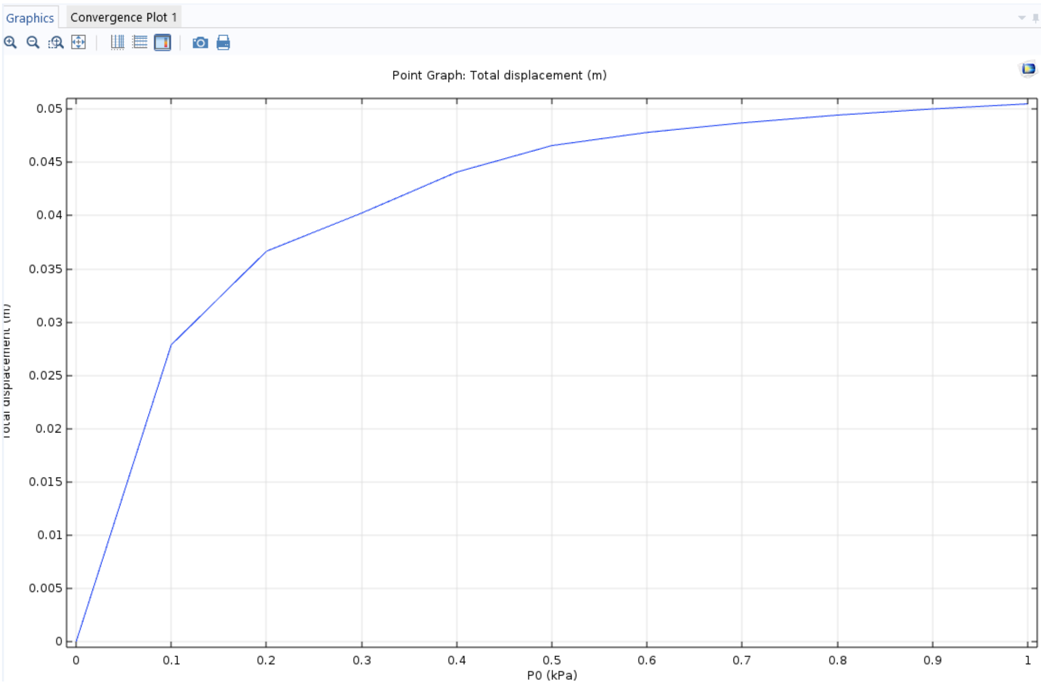

Figure 37: Displacement versus load when negative load is applied.

4.6 Relationship of Voltage and IPMCs Length

Figure 42 until Figure 45 shown a structure of the IPMCs with five difference length from 20.07mm, 30.07mm, 40.07mm and 50.07mm respectively. The constant load of 0.5kPa was applied on top of the IPMCs tip. From those figures, the bending of a IPMCs was reduced as the length of the IPMCs reduced. This can be seen by comparing the Figure 42 with Figure 45. With the length of 20.07mm, the structure of the IPMC only bending around 15^{o} from the original position. Whereas, it was bending more than 90^{o} with the length of 50.07mm. The longer of the IPMCs structure will cause the IPMCs tips more flexible because of the large surface area. So, the smaller load was able to bend the IPMCs structure as shown in Figure 45.

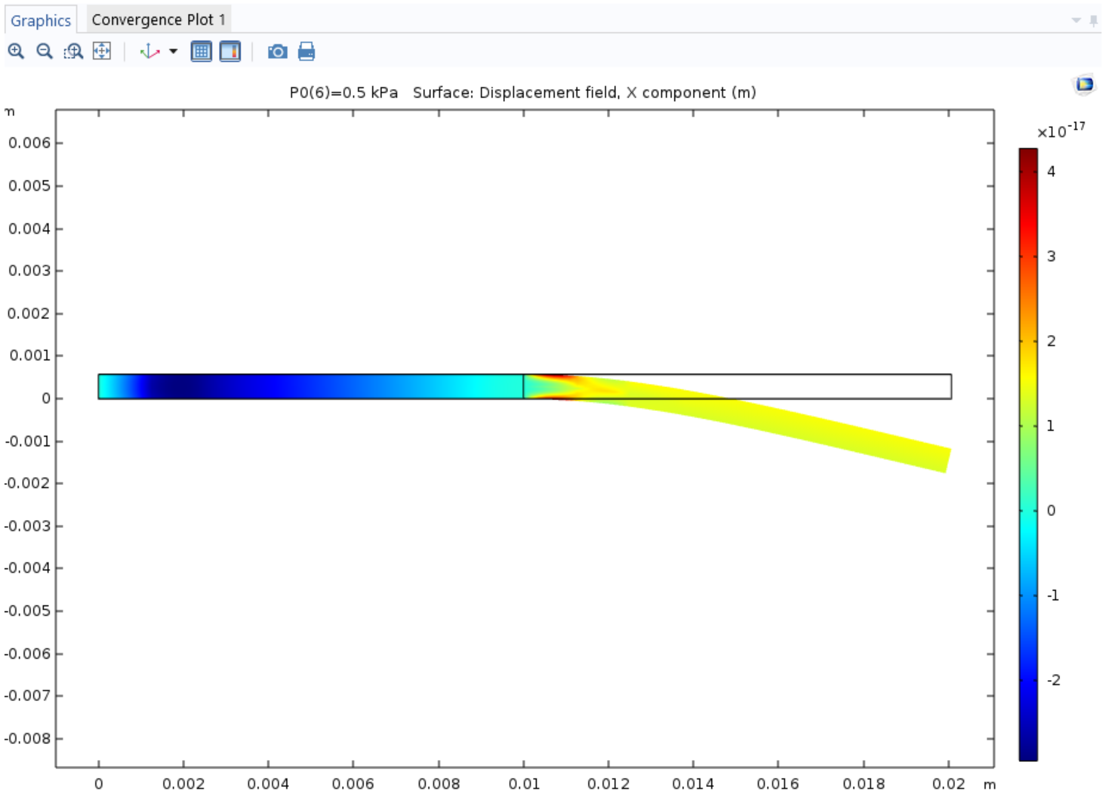

Figure 38: Structure of the IPMCs with a length of 20.07mm when 0.5kPa load was applied.

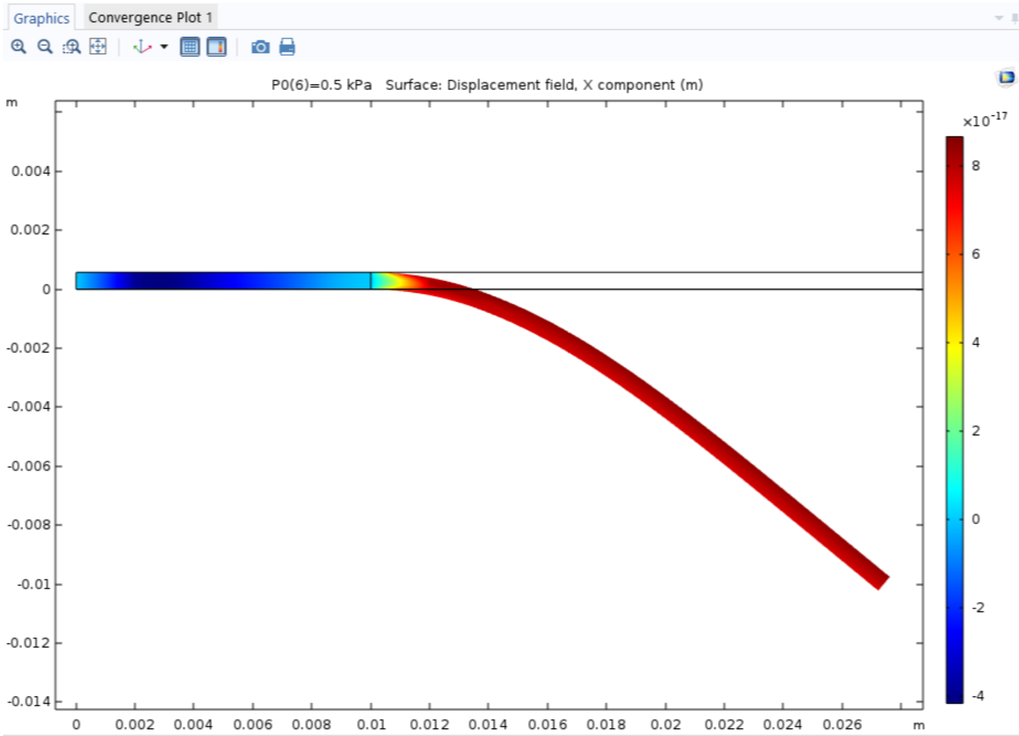

Figure 39: Structure of the IPMCs with a length of 30.07mm when 0.5kPa load was applied.

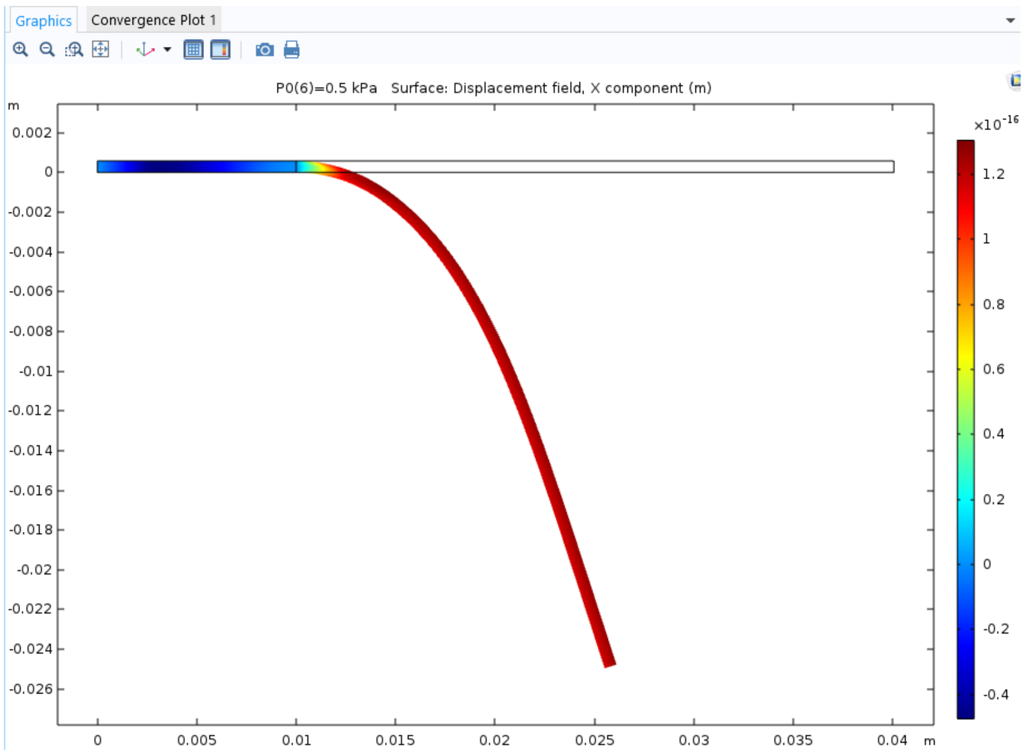

Figure 40: Structure of the IPMCs with a length of 40.07mm when 0.5kPa load was applied.

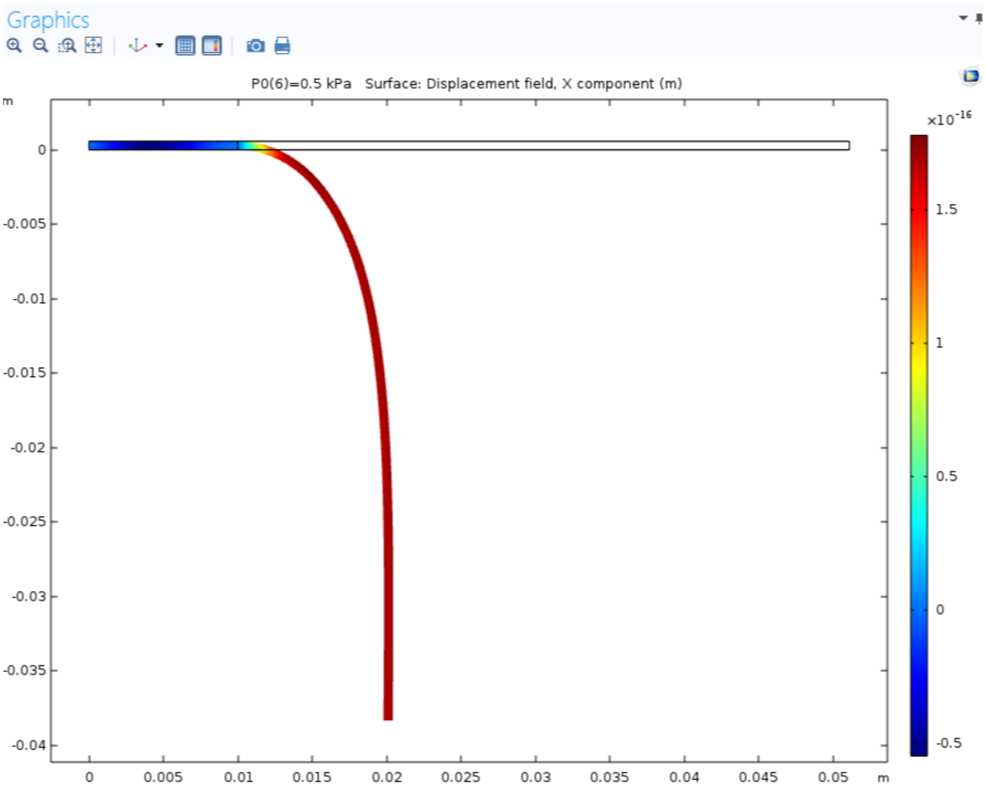

Figure 41: Structure of the IPMCs with a length of 50.07mm when 0.5kPa load was applied.

Table 2: An output voltage with a difference length of IPMCs at 0.5kPa.

Length (mm)	**Output voltage (mV)**
20.07	3.2
30.07	9.8
40.07	15.8
50.07	22.5

As shown in Table 2, the output voltage was increased as the length of the IPMCs increased. IPMCs with a length of 20.07mm, 30.07mm, 40.07mm, 50.07mm and 50.07mm produced an output voltage of 3.2mV, 9.8mV, 15.8mV, 22.5mV and 29.0mV respectively. Therefore, we can conclude that the output voltage produce was directly proportional to the length of the IPMCs. The large bending of the IPMCs structure on the longer length was a main factor to produce the large output voltage. Figure 42 until Figure 45 shown the output voltage of the IPMCs with a difference length and difference load applied on the IPMCs.

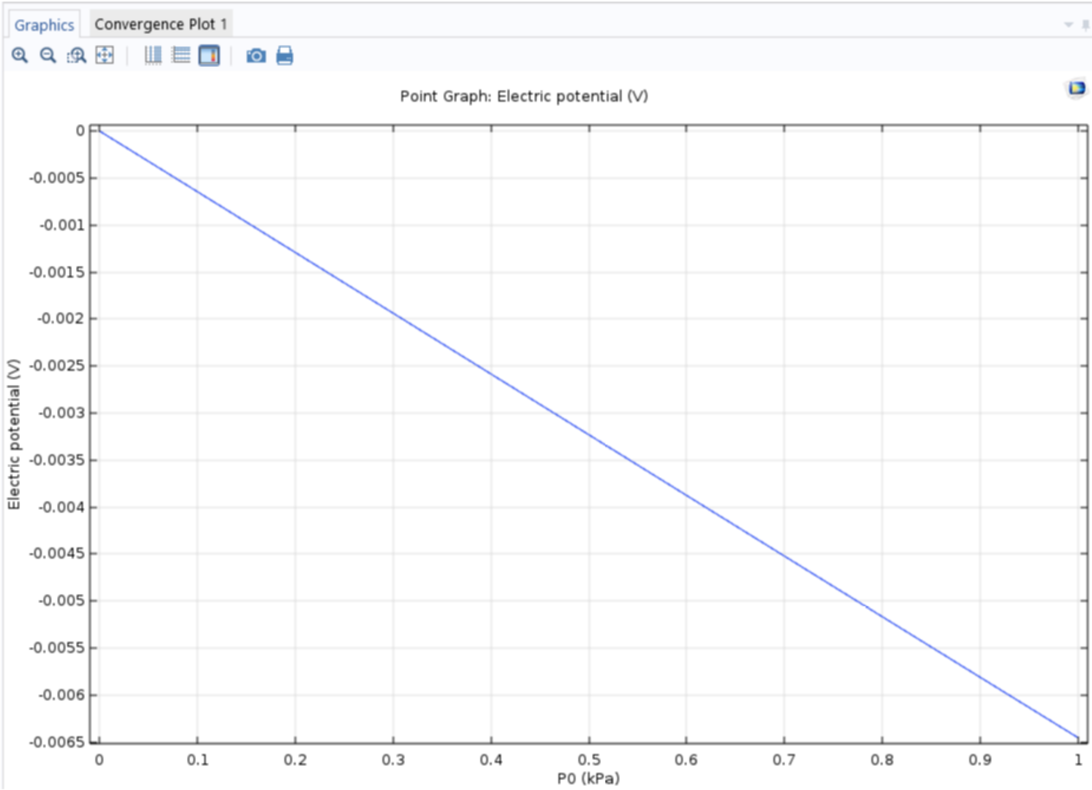

Figure 42: Output voltage of IPMC with the length of 20.07mm.

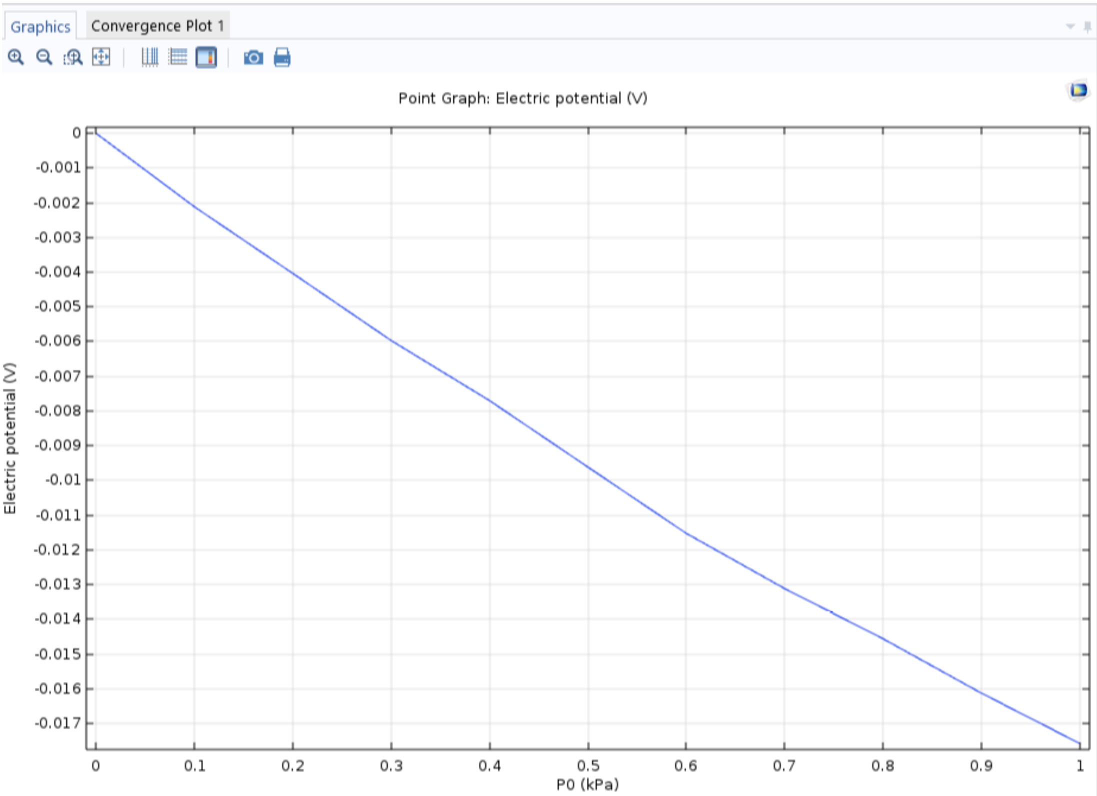

Figure 43: Output voltage of IPMC with the length of 30.07mm.

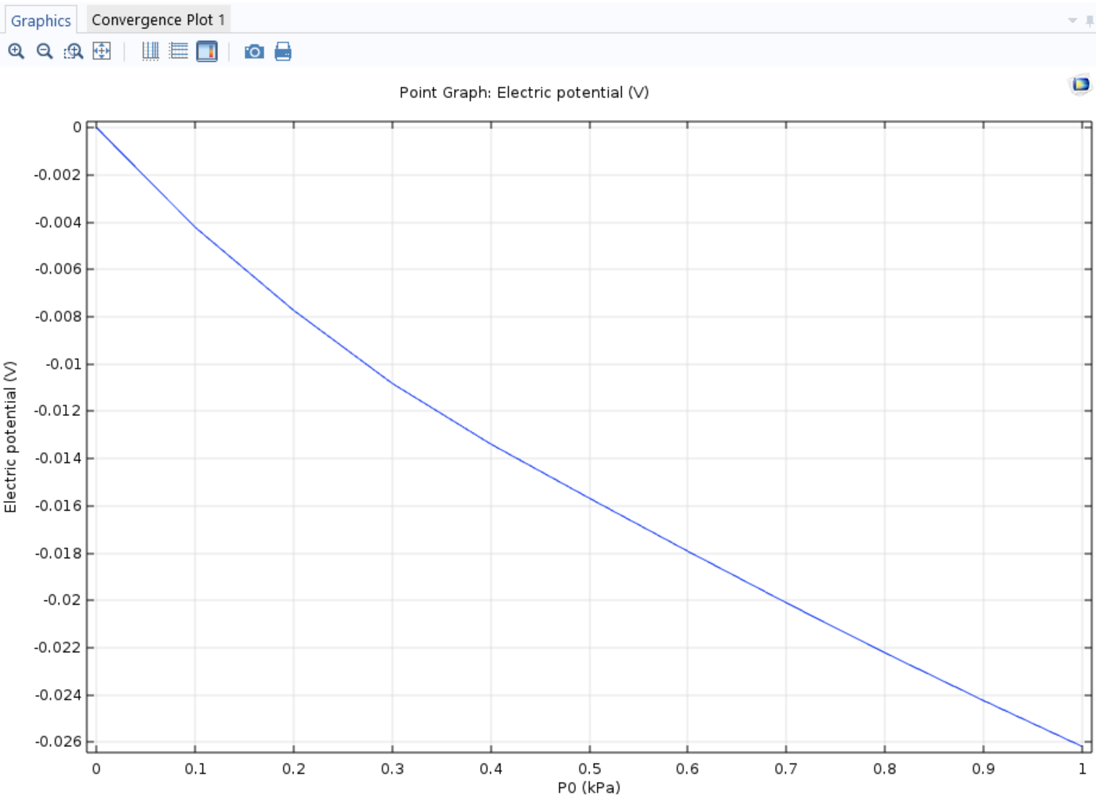

Figure 44: Output voltage of IPMC with the length of 40.07mm.

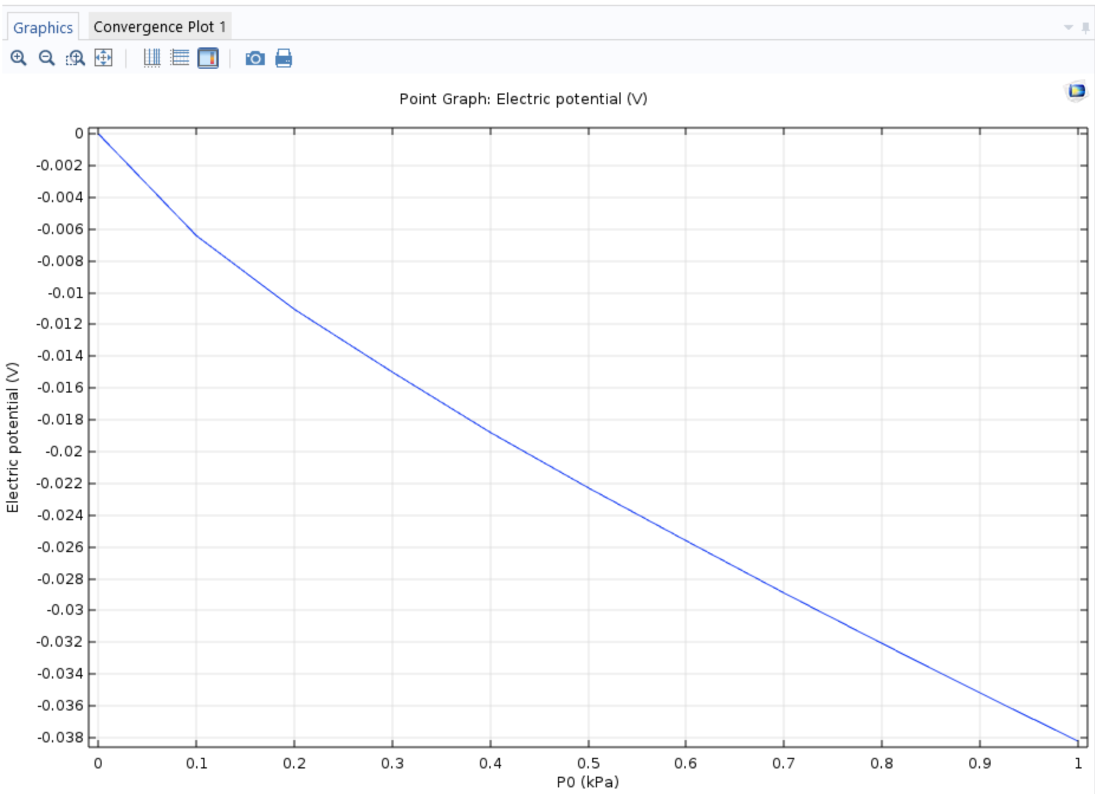

Figure 45: Output voltage of IPMC with the length of 50.07mm.

4.7 Relationship of Voltage and IPMCs Thickness

Figure 47 until Figure 49 shown a structure of the IPMCs which the difference thickness from 0.296 mm, 0.586 mm and 1.016 mm respectively. The IPMCs with a thickness of 0.296 mm bent around 90º from the original position. The bent degree was reduced as the thickness of the IPMC reduced. The thinner structure of IPMCs will cause the structure more flexible.

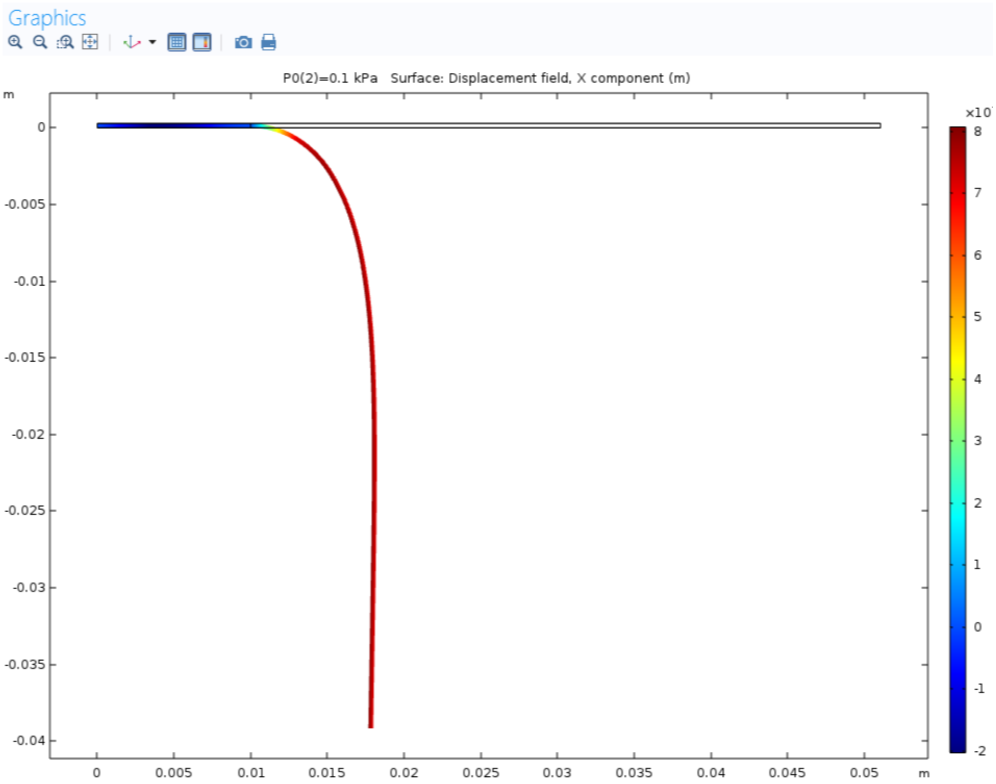

Figure 46: Structure of the IPMCs with a thickness of 0.296mm when 0.1kPa load was applied.

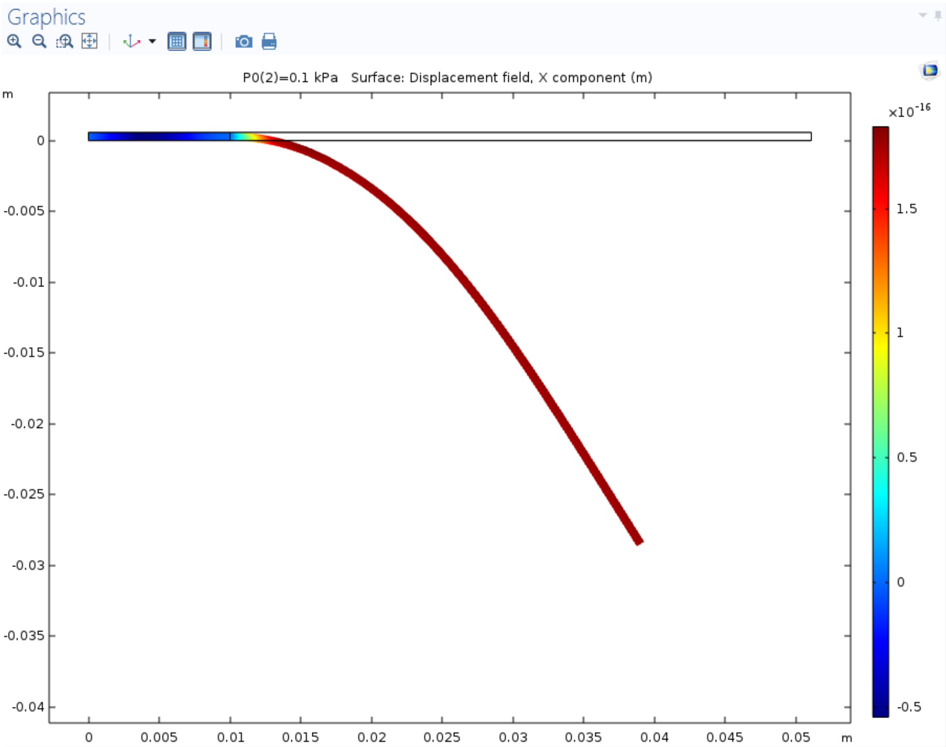

Figure 47: Structure of the IPMCs with a thickness of 0.586mm when 0.1kPa load was applied.

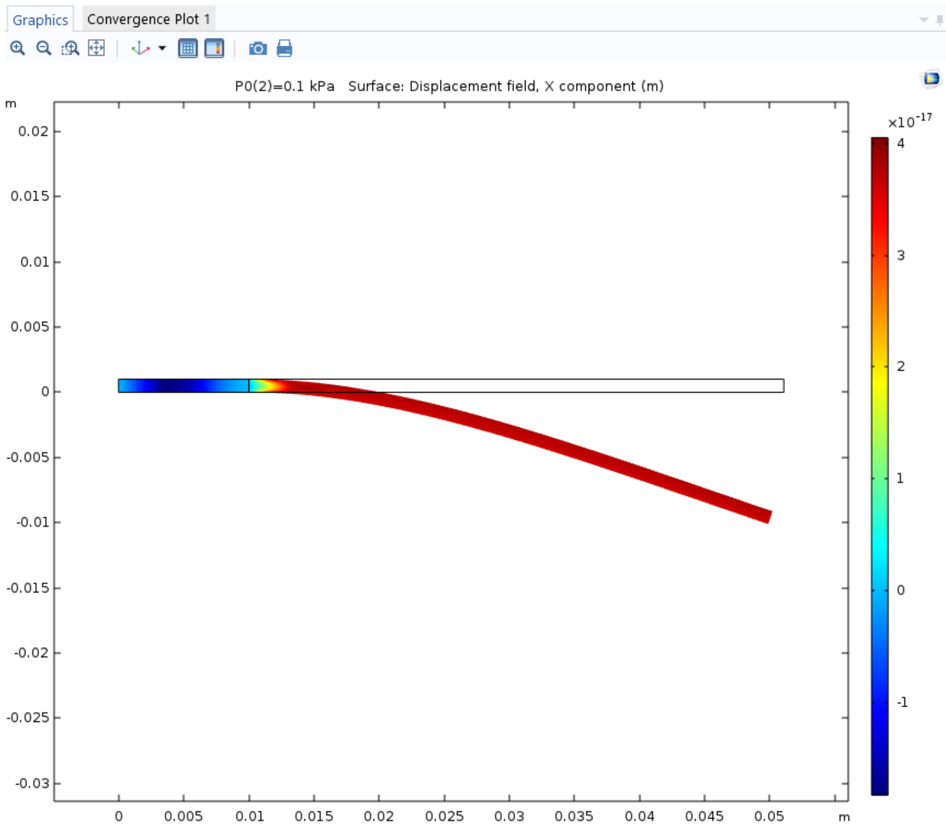

Figure 48: Structure of the IPMCs with a thickness of 1.016mm when 0.1kPa load was applied.

Table 3: An output voltage with a difference thickness of IPMCs at 0.1kPa.

Thickness (mm)	**Output voltage (mV)**
0.296	8.2
0.586	2.2
1.016	1.2

As shown in Table 3, the output voltage was decrease as the thickness of the IPMCs increased. IPMCs with a thickness of 0.296mm, 0.586mm, and 1.016mm produced an output voltage of 8.2mV, 2.8mV and 1.2mV respectively. Therefore, we can conclude that the output voltage produce was inversely proportional to the length of the IPMCs. The large bending of the IPMCs structure on the longer length was a main factor to produce the large output voltage. Figure 50 until Figure 52 shown the output voltage of the IPMCs with a difference thickness and difference load applied on the IPMCs.

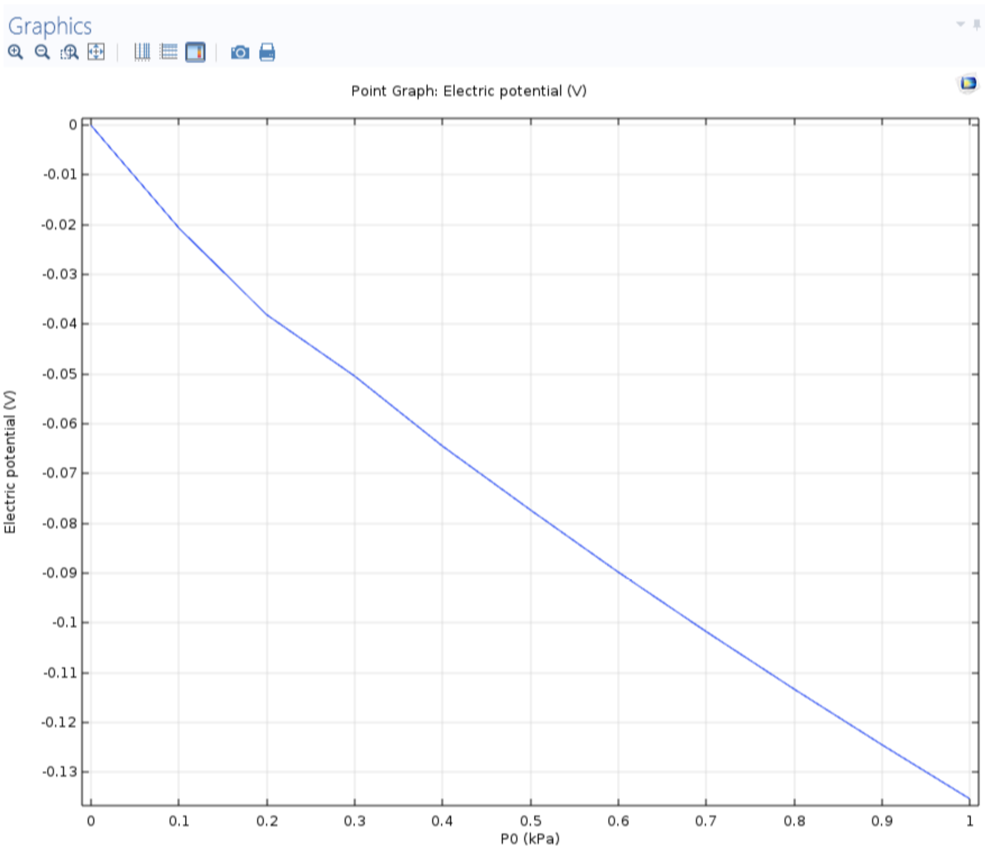

Figure 49: Output voltage of IPMC with the thickness of 0.296mm.

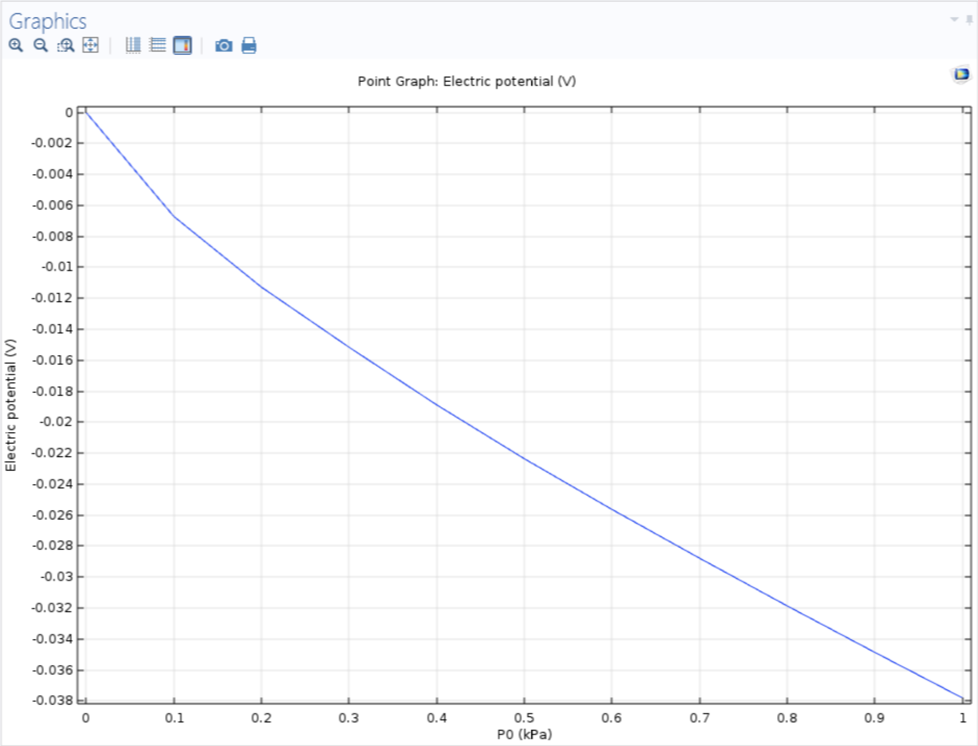

Figure 50: Output voltage of IPMC with the thickness of 0.586mm.

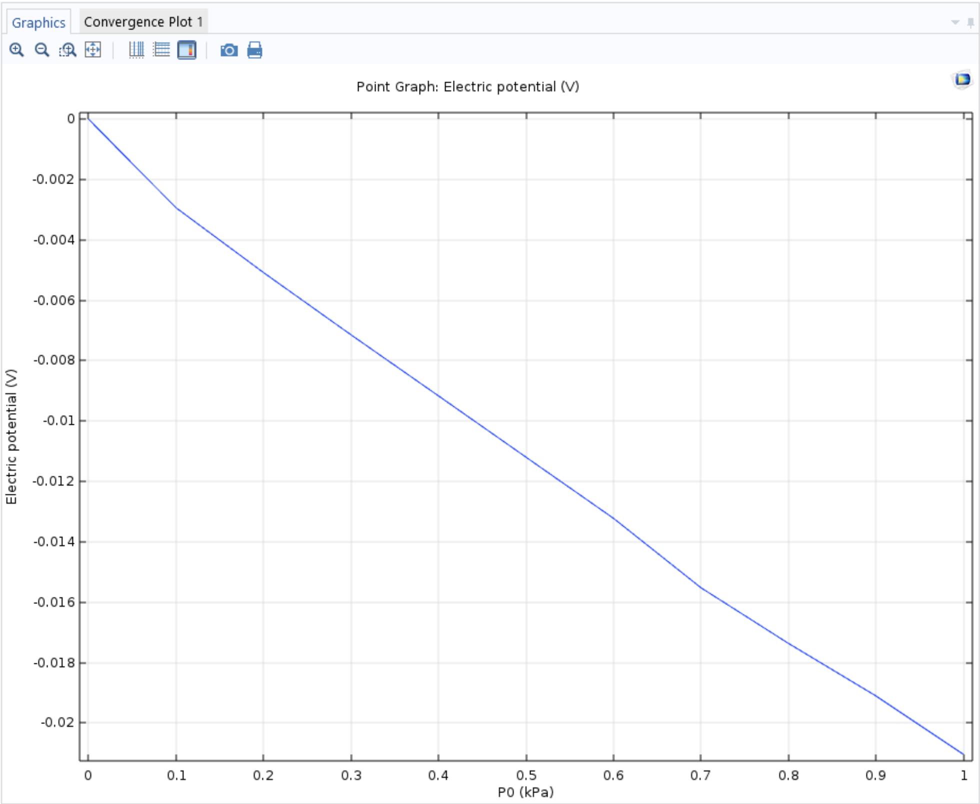

Figure 51: Output voltage of IPMC with the thickness of 1.016mm.

4.8 Summary

The simulation of the IPMC material as a sensor was presented. From the result, IPMC was able to use as a sensor. However, the low electrical output of the sensor required an additional study to overcome the overlapping with the other noise.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research demonstrates the simulation of an IPMC as a sensor. From the simulation result, the IPMC was able to use as on a sensing application or energy harvester (Aw and Praneeth, 2013; Patel and Mukherjee, 2018). The displacement of the IPMC movement will produce an electric signal that can be used to sense the movement.

5.2 Recommendations for future work

The future study can be done on the research by correlate this simulation with the actual result. The setup of actual testing can be done by create the actual size of the IPMC and applying the force test as shown in Figure 48 (Hunt *et al.*, 2009; Bhandari, Lee and Ahn, 2012; He *et al.*, 2019).

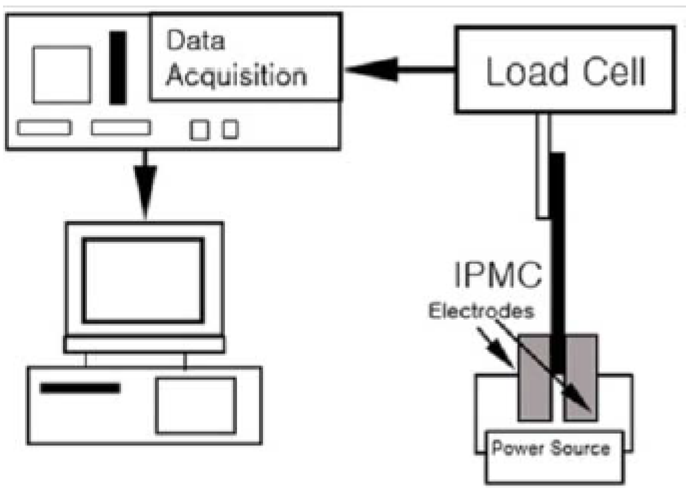

Figure 52: Schematic diagram of the setup testing by using force on the IPMC tip.

Besides that, the future study on the difference material used as a metal, shape of the IPMC and the lifetime of the IPMC performance to degrade also required to improve the performance and stability of the IPMC.

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