# ROBUST MICROFLUIDIC FLOW SENSOR WITH A BIOLOGICALLY-INSPIRED CUPULA STRUCTUREFOR FLOW RATE MEASUREMENT



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SULTAN IDRIS EDUCATION UNIVERSITY

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Author

## ABSTRACT

This research is about the development of robust microfluidic flow sensor with a biologically-inspired cupula structure for flow rate measurement. The proposed flow sensor consists of a dome-shaped structure, microchannel and coplanar electrode. Mechanical analysis of the dome-shaped membrane is carried out by using finite element analysis in terms of deflection and Misses Stress. The simulations using Ansys software were carried out for both Computational Fluid Dynamic (CFD) and Finite Element Analysis (FEA). A sensor with a 3.2 mm radius of dome and 0.5 mm in dome thickness had been selected from the simulation due to its flexibility. The mold of the flow sensor was designed by using Solidwork® 2016 and fabricated using soft lithography process including casting and molding process in Polydimethysiloxane (PDMS) structure fabrication. The electrode was fabricated by using Printed Circuit Board (PCB) process. It was design by using EAGLE software. There were a few processes that involved in PCB process which were printing process, exposure process, developer process and etching process. Last process is a sealing process, where both fabricated PDMS structure and electrode were seal and carefully aligned. Polydimethylsiloxane (PDMS) is used as a membrane due to its high elasticity compared to other polymers. Propylene carbonate (PC) electrolyte is used for its high dielectric constant that gives good performance in terms of its high boiling point which improves the longevity of the liquid inside the microchannel. Based on the experimental results, the operating frequency and the flow rate of the flow sensor were ideally observed at 4.4 kHz and between 0 to 0.17 $\mu m^3$/s. The effects of temperature and pressure were recorded and discussed in this research.

**PENDERIA ALIRAN LASAK DENGAN STRUKTUR KUPULA YANG DIINSPIRASIKAN SECARA BIOLOGI UNTUK PENGUKURAN KADAR ALIRAN**

## ABSTRAK

Kajian ini bertujuan untuk membina penderia aliran yang lasak dengan struktur kupula yang diinspirasikan secara biologi untuk pengukuran kadar aliran. Penderia aliran mempunyai bentuk kubah, saluran mikro dan elektrod koplanar. Analisis mekanikal membran berbentuk kubah dijalankan dengan menggunakan analisis unsur terhingga dari segi pesongan dan Misses Stress. Kaedah simulasi yang digunakan bagi *Computational Fluid Dynamic* (CFD) dan *Finite Element Analysis* (FEA) ialah dengan menggunakanperisian 'Ansys'. Penderia aliran dengan kubah berjejari 3.2 mm dan 0.5 mm ketebalan telah dipilih daripada simulasi kerana tidak mudah koyak. Acuan penderia aliran telah direka bentuk menggunakan Solidwork® 2016 dan dibina menggunakan proses 'Soft Lithography' iaitu melibatkan proses 'casting' dan 'molding' bagi pembinaan struktur Polydimethysiloxane (PDMS). Elektrod telah dibina dengan menggunakan proses 'Printed Circuit Board (PCB)'. Elektrod telah direka bentuk menggunakan perisian EAGLE. Terdapat beberapa proses yang melibatkan proses PCB iaitu proses mencetak, proses pendedahan, proses membangun dan proses penggoresan. Proses terakhir merupakan proses pencantuman di mana struktur PDMS yang telah dibina dicantumkan selari dengan elektrod. Penderia aliran telah direka bentuk menggunakan perisian Solidwork® 2016 dan dibina menggunakan kaedah 'molding' dan proses 'sealing'. PDMS telah digunakan sebagai membran kerana factor kekenyalan yang tinggi berbanding polimer yang lain. Propylene carbonate (PC) telah digunakan kerana mempunyai pemalar dielektrik yang tinggi kerana mempunyai takat didih yang tinggi membantu cecair bertahan lama di dalam saluran mikro. Berdasarkan keputusan eksperimen, frekuensi dan kadar aliran penderia secara ideal ialah pada 4.4 kHz dan kadar antara 0 hingga 0.17 $\mu m^3$/s. Kesan suhu dan tekanan telah direkod dan dibincangkan di dalam kajian.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| PDMS | Polydimethysiloxane |
| PC | Propylene carbonate |
| HVAC | Heating, ventilation, air conditioning |
| PCB | Printed circuit board |
| MEMS | Micro electromechanical system |
| NEMS | Nano electromechanical system |
| CFD | Computational fluid dynamic |
| FEM | Finite element method |
| EDLC | Electrical double layer capacitance |
| PVDF | Polyvinyl fluoride |
| VACNT | Vertically aligned carbon nanotube |
| PU | Polyurathene |
| PI | Polyimide |
| FEA | Finite element analysis |
| UV | Ultraviolet |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background



Flow sensors are becoming greater significance for many applications and have been used in maneuvering system for underwater autonomous vehicles. Flow sensors have aspects such as low detection threshold, short response time, less intrusion to the flow field of interest and high robustness, all of which are needed for certain applications (Tao & Yu, 2012). Surveillance of the subsea environment was greatly supportive by underwater surveillance methods (Sevaldsen, 1993). The flow sensors usually perform such maneuvering in an array, which may be used to guide an autonomous underwater vehicle to find out the distance, location and direction of moving objects in an absence of light environment (Coombs, 2001; Yang et al., 2011). Global industries call for underwater technology applied to several scenarios such as monitor the environment and monitor the underwater structures (Hasan et al., 2017). Maritime unmanned systems can be used to give a solution of the problems by looking through recent advances in marine robotics (Ferri et al., 2017). Target detection, localization and tracking are several issues that need to be considered with surveillance systems (Munasinghe et al., 2017). In addition, depth also needs to be known, because different depths influence the physical process in water environment (Aravamudhan & Bhansali, 2008; Kottapalli etal., 2016). This can be done using a pressure sensor to monitor the depth level for underwater vehicles.

The nowadays invention relates to the medium of air velocity or flow sensors that are available commonly of the single hot wire or thermistor type. It is also typically set up on the end of a long probe for insertion into the air mainstream. Flow sensors are used in respiratory devices and inhalers, insufflators and aesthetic devices. It is being used all over the world, including the industrial processes, medical technology and in heating, ventilation and air conditioning (HVAC) and smart energy applications. Gas analyzers, fuel cells, process control, low vacuum control, filter monitoring, gas measuring stations or extraction hoods are other applications of these sensors. The expanding applications in the healthcare electronic equipment and devices that are used to sense and monitor temperature, chemicals, pressure, positions and other biological indicators is increasing rapidly with the global flow sensor.

Besides that, flow sensors are sensors that function to measure fluid flow rate and these are the generally part of a flow meter that has been studied. There are several types of flow sensors in the flow sensor field which have different function and motive. Multiple directions is the most important in the capability of the flow sensors to perform the measurement but current hair cell sensors are only capable of performing measurements in a single direction (Chen et al., 2007; Tao & Yu, 2012; Nguyen et al., 2014). The cantilever beam structure of hair cell gives a limitation for multidirectional flow sensing. Flow measurement is necessary for different engineering operations and it is also the diverse area. Dissimilar types of flow sensors gives dissimilar types of application such as chemicals, gas meter, process auto-control, food, medical and beverages. There are four types of flow sensors which are famous and broadly used such as oval gear flow meter, turbine flow sensor, resistance, temperature and water flow sensor and detector (RTD) sensor. Oval gear flow meter is to measures flow when it passes through a magnetic pick-up sensor use for measuring rotation quantity of gear and a chamber. Turbine flow sensor is to measure the velocity of liquid in the rotor shaft movement which available to measure the flow in both backward and forward direction. RTD sensor consists of wire made from pure metal like platinum or copper and its function is to measure the temperature. Water flow sensor is to measure the water flow in pulse rate output and involve in injection molding machine and other tools. Therefore, a cupula shaped like a dome was proposed due to its symmetrical structure in order to overcome this problem. Current flow sensors are only focused on the piezoresistive and strain gage where the fabrication of these types of sensing elements uses silicon as a main material and involving a complex fabrication technique, such as depositions and sacrificial layer etching, which require more specific control (Suter et al., 2013)

Microfluidic devices have enabled miniaturized biochemical analysis and chemical applications for over the past 15 years (Dittrich et al., 2006). Efficient manipulations of fluid flow have been broadly used by using microfluidic techniques in micro scale for biomedical research and analytical chemistry (Zarifi et al., 2018). Besides that, microfluidic devices permit spatially precise, temporally and reproducible fluid delivery (Amarie et al., 2007). Nowadays, microfluidics gives more specifically for biological analysis and efficient tools for multiple research areas such as low reagent consumption, global cost reduction per analysis, portable devices for point-of-care applications and many more.

In microfluidic flow sensor, there are many designs that had been fabricated through the past years by researcher. In the last decade, biological inspiration such as fish lateral line sensing mechanism has provided a different way to improve the performance of the sensor. Blind cave fish which has a lateral line system live in low light environments that can function to move and detect the prey (Bleckmann, 1993). A lateral line system consists of two types of neuromast that are a canal neuromasts, which has gelatin dome structure an superficial which are more like cilia (Coombs, 2001). Both canal and superficial neuromasts have a gelatin cupula which transfer the movement to sensory hair cells to induce a neuron signal and moves based on flow pressure (Engelmann et al., 2002). Cupula which is neuromast covers thesensory organof fishes and is has two types of neuromast that is canal neuromast (CNs) and superficial neuromast (SNs) (Bora et al., 2017). Hence, the development of novel sensors is to apply design from natural sensors to artificial engineering materials and it has high sensitivity and performance (Bora et al., 2017). Electrospun micro/ nano fibers and hydrogel capping and were used for mimicked cupula and copular fibrils in microfabricated sensors field (Kottapalli et al., 2016).

In the present work, a portable, robust and scalable flow sensor depends on microwave and microfluidic technologies that are presented for the long-term, realtime, nonintrusive detection and noncontact of flow rate in microfluidic environment (Zarifi et al., 2018). The multivariable applications of microfluidics have been view to carry out screening, analysis and detection of biomaterial and chemical samples with discretequantities (Salim & Lim, 2018). For fabricate robust microfluidics flow sensor, it requires an analysis of the design, operating frequency, temperature, life time, pressure measurement and flow measurement that corresponding to the flow sensor.

## 1.2 Problem Statement

Generally, a capacitive-type sensor consists of parallel of two electrodes which is one electrode is movable while the other is fixed. When the pressure applied to the membrane, it deforms and displaces. The movable electrode is sensed and capacitance changes depend on both the distance and contact surface area between the two electrodes. Capacitive-type sensor needs a technique with 2D or 3D structure in a micro scale. So, the common techniques to fabricate the electrode by using micro-electromechanical system (MEMS) which is the common techniques for micromachining.

However, this design is difficult to miniaturize due to the complexity of fabrication process. It is because the fabrication techniques require deposited and sacrificial layers adjustment for mechanical properties and consistency (Suter et al., 2013). Therefore, Polydimethylsiloxane (PDMS) is proposed as a main material where PDMS can easily create any type of geometry for various applications. An experiment on the sensor using other types of liquid will be carried out to enhance the sensor performance, especially to improved longevity.

Microfluidic flow sensor need to be in a robust state for higher performance. One of the robust characteristics is chemical compatibility as it can lead to flow sensor's performance. Based on the previous research by Bora et al. (2017), fish- inspired flow sensor was built by using silicone material. It has cupula structure at the centre of the flow sensor and consists of silicone material as the base of the sensor. Canal neuromats consist of cupula structure which sensitive to flow velocity, (Coombs, 2001). Canal neuromast consist of dome shaped structure similar to cupula. PDMS was one of the major materials used in poly microfluidics because of material elasticity and gas permittivity. Larger deformation of shows a higher sensitivity of PDMS than silicon-based because of the lower Young's modulus of the PDMS (Lee et al., 2008).

## 1.3 Objective Research

The main objective of this research is to develop a robust microfluidics flow sensor with a biologically-inspired cupula structure for underwater surveillance.

Three sub-objectives are as follows:

a) To design flow sensor based on the cupula structure and microfluidic technology.

b) To fabricate the flow sensor using PDMS based on soft lithography technique.

c) To characterize the flow sensor for pressure, temperature effect and flow rate measurement.

## 1.4 Scope of Study

The main focus of this research is the development of fluidic flow sensor including designing, fabrication and characterization. Designing the PDMS structure membrane by using Autodesk Inventor 17 for the molding of the dome-shaped membrane.

The dome-shaped structure was studied based on the deflection, strain and stress. Material that has been selected as the membrane was Polydimethysiloxane (PDMS). Surface roughness inside the channel was not considered. Besides that, fluid structure interaction during liquid movement also does not consider.



For the fabrication, PDMS was selected as a material for fluidic flow sensor. It was fabricated in room temperature condition. The mold was fabricated using 3D printing machine for rapid fabrication. The modification of the membrane fabrication process was carried out using molding process and electrode printing process by using printed circuit board (PCB) of coplanar electrode. The temperature effects during fabrication process were not studied in this fabrication process. The fabrication process is completed by sealing the container with the coplanar electrode placing side by side on the FR-4 material of coplanar electrode in microchannel pattern.

For the characterization, it has been focused on fluidics flow sensor. Fluidics flow sensor has a dome-shaped membrane, channel and liquid. The experiment was carried out for operating frequency with one type of liquid and pressure measurement. The fluid mechanism, linearity and temperature for pressure measurement, flow measurement and lifetime of liquid are also included.

## 1.5 Summary of Contribution

In this research, dime-shaped membrane was developed for flow measurement using a fluidic system. The sensing mechanism was realized using coplanar electrode to create a form an ionic layer. Besides that, using this concept created the value of capacitance. This concept of sensing has been proved appropriate for flow measurement. The summary of the contributions of this study are:

Fluidic flow sensor using a PDMS container that offers simple structure and sensing. It also used small amount of liquid for flow measurement. PDMS was chosen as the material of the membrane. It was easy to fabricate using molding process and electrode printing was performed using printed circuit board (PCB).

## 1.6 Thesis Organization

Chapter 1 provides an overview of the fluidic flow sensor. The problem statements, research objectives, research scope and a summary of contribution were also presented.

Chapter 2, presents the literature review which includes the flow sensor in underwater surveillance, principle of sensor, material used and fabrication process, microfluidic based sensor and characterization.

Chapter 3, primarily concerned with the design and methodology employed in this research study for the fabrication process. A simple fabrication process for the sensor using PDMS material and electrode printings are explained and the characterization of the sensor was also included in this chapter.



Chapter 4, the result and discussions obtained from the fabrication and characterization. The fluid mechanism test of the flow measurement was implemented with a fluidic system for the coplanar electrode.

Chapter 5, the research and provide future research recommendations for enhancement of a fluidic flow sensor.