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***Study of Magnetic Nanoparticle Composite Polymer thin  
layer for Microfluidic and MEMS applications***

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## المخلص

مختبر على رقاقة أو معمل على رقاقة أو المعمل على رقاقة هو جهاز يجمع بين وظيفة أو عدة وظائف المختبر على رقاقة واحدة باستعمال اجهزة علم الموائع الدقيقة مثل المضخات و الصمامات الدقيقة , التي تتحكم في الموائع في القنوات (خلط, ضخ, او تغير اتجاه), المكون الاساسي في اجهزة علم الموائع الدقيقة هي الطبقات الرقيقة المتحركة, التي عادة ما تكون مصنوعة من البوليمر. تم اعتماد مبادئ تحريك مختلفة , مثل الكهرباء أو الحرارة أو الكهروضغطية. ومع ذلك , فإن هذه الأساليب تفرض قيودًا متنوعة , مما يجعل استخدامها المباشر صعبًا. يُظهر التحريك المغناطيسي نتائج مثيرة للاهتمام بسبب نقص التوصيلات الكهربائية , وإمكانية التلاعب بها على مسافة كبيرة , والاستجابة السريعة للمجال المغناطيسي الخارجي. الهدف من هذه الأطروحة هو محاكاة الاستجابة المغناطيسية للطبقات الرقيقة المركبة من البوليمر والجسيمات النانوية المغناطيسية , وتطبيقها في آلية المضخة الدقيقة باستخدام برنامج المحاكاة .COMSOL Multiphysics.

## Abstract

A lab-on-a-chip (LOC) is a device that offers one or several laboratory functions using microfluidic devices such as micropump, microvalves ... etc., which manipulate fluid in microchannel (mixing, pumping, change direction ...etc), and the important component in microfluidics devices are the actuated membrane, which are generally made of polymer. Various actuation principles have been adopted, including electrostatic, thermal, or piezoelectric. However, these methods present diverse limitations, making their direct utilization difficult. The magnetic actuation shows an interesting result because of the lack of electrical connections, the possibility of being manipulated at a large distance, and the fast response to the external magnetic field. The aim of this thesis is to simulate the magneto-responsivity of a magnetic nanoparticle-polymer composite membrane, and their application in a micropump mechanism using COMSOL Multiphysics.

## Résumé

Un laboratoire intégré sur une puce est un dispositif qui offre une ou plusieurs fonctions de laboratoire utilisant des dispositifs microfluidiques tels que les micropompes, et les microvannes, etc., qui manipulent le fluide en microcanal (mélange, pompage, changement de direction...), et le plus important composant dans les dispositifs microfluidiques sont les membranes actionnées, qui sont généralement en polymère. Divers principes d'actionnement ont été adoptés, notamment électrostatique, thermique ou piézoélectrique. Cependant, ces méthodes présentent diverses limitations, ce qui rend leur utilisation directe difficile. L'actionnement magnétique montre un résultat intéressant en raison du manque de connexions électriques, de la possibilité d'être manipulé à grande distance et de la réponse rapide au champ magnétique externe. Le but de ce mémoire est de simuler la réponse magnétique d'une membrane composite polymère-nanoparticules magnétiques, et leur application dans un mécanisme de micropompe utilisant COMSOL Multiphysics.

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Especially in quarantine time, where the experimental aspect of this project was planned to be implemented in CRTI Research Center, but corona virus circumstances, confined us to perform a simulation aspect via comsol multiphysics. So, we would like to thank **Dr. Abdelrahmane Younes** and the CRTI Research Centre for giving us this opportunity, and for their advices.

We would like to take this opportunity to say warm thanks to all our beloved family and friends, who have been so supportive along the way of doing my thesis.

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Finally, our thanks go to all the people who have supported us to complete the research work directly or indirectly.

# DEDICATION

This thesis is dedicated to:

my parents, who raised me with a love of science  
and supported me in all my pursuits.

my sister and brothers, whom I am truly grateful  
for having in my life.

my loving and encouraging family & friends.

My dedication also goes out to everyone with  
whose effort the completion of this thesis was made  
possible.

***Ahmed Rafik Touil***

# DEDICATION

This thesis is dedicated to:

My great parents, who never stop giving of

themselves in countless ways,

My beloved brothers and sisters

My friends who encourage and support me,

All the people in my life who touch my heart, I

dedicate this research.

***Rokia Belgacem***

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# **CHAPTER 1: OVERVIEW ABOUT MICROFLUIDIC DEVICES**

## 1.1 Introduction

During the last two decades, MEMS research has been largely encouraged by the first introduction of miniaturized total analysis systems by Manz et al to the MEMS community. They are widely employed in areas from biomedical and drug delivery to space and fuel cell microfluidic systems. These systems have been reduced in size to micro scale for the realization of a fully integrated microfluidic system, such as lab-on-a-chip (LOC) or a micro total analysis system ( $\mu$ TAS) [1]. In this chapter, microfluidics devices are highlighted, beginning with MEMS definition, then microfluidics and their physical concepts, major devices, and applications and eventually, giving an overview about membrane technology.

## 1.2 What is MEMS?

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of microfabrication. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move [2]. Figure 1-1 shows the development of MEMS devices in time.

The term used to define MEMS varies in different parts of the world. In the United States they are predominantly called MEMS, while in some other parts of the world they are called “Microsystems Technology” or “micromachined devices” [2].

While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the microsensors and microactuators. Microsensors and microactuators are appropriately categorized as “transducers”, which are defined as devices that convert energy from one form to another. In the case of microsensors, the device typically converts a measured signal (including temperature, pressure, inertial forces, chemical species, magnetic fields, radiation, etc.) into an electrical signal [3].

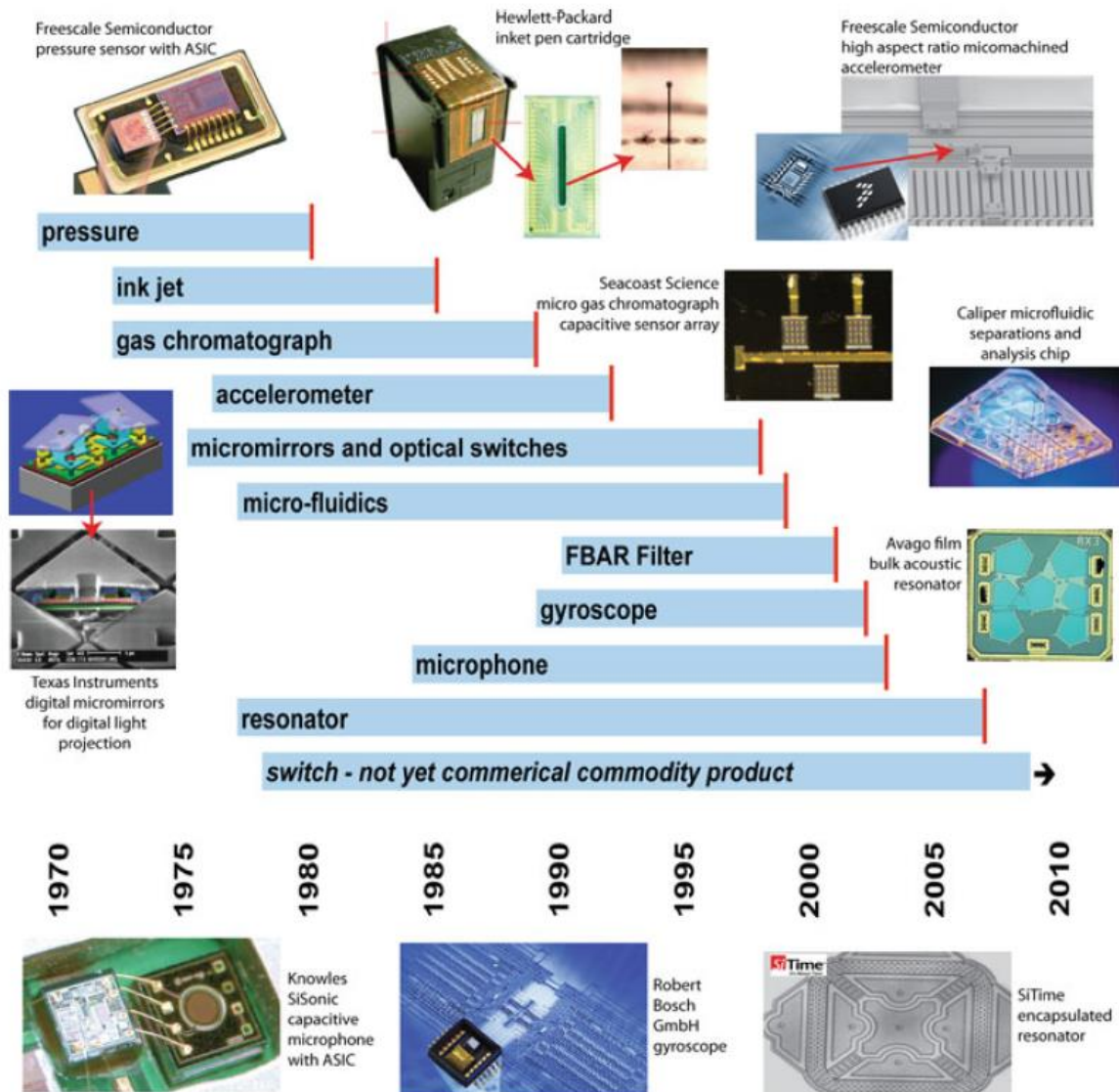


Figure 1-1: Timeline of research and development cycles from first research reports to first commercialization of several MEMS products [4].

### 1.2.1 Transducers

Transducers have become an integral part of everyday life. A transducer is a device that transforms energy from one domain into another. Typical energy domains include mechanical, electrical, optical, magnetic, and thermal. Figure 1-2 shows the energy-conversion process among domains. The transducer can also be visualized as having at least two locations or ports at which it exchanges energy with the environment [5]. Transducers may generally be divided into two classes: sensors, which monitor a system; and actuators, which impose a condition on a system.

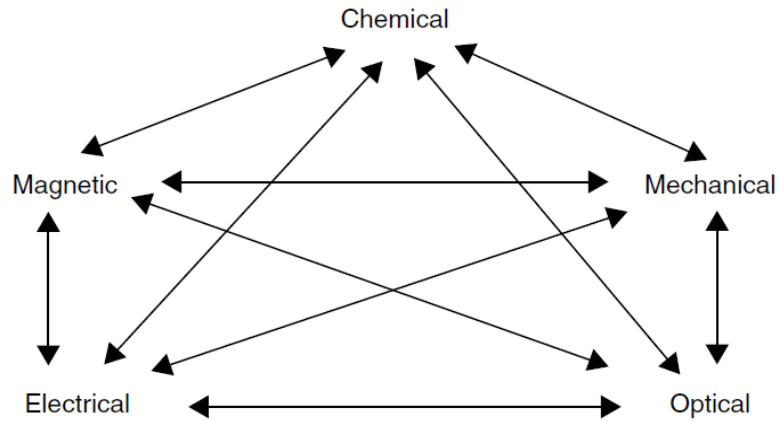


Figure 1-2: Definition of transducer [5].

### 1.2.1.1 Sensor

Sensor is a device that when exposed to a physical phenomenon (temperature, displacement, force, etc.) produces a proportional output signal (electrical, mechanical, magnetic, etc.). As mentioned earlier, the term transducer is often used synonymously with sensors. To reiterate, a sensor is a device that responds to a change in the physical phenomenon. On the other hand, a transducer is a device that converts one form of energy into another. Sensors are transducers when they sense one form of energy input and output in different form of energy [5].

For example, a thermocouple responds to a temperature change (thermal energy) and outputs a proportional change in electromotive force (electrical energy). Therefore, a thermocouple can be called as a sensor and or a transducer [5].

Sensors can be classified based on (a) what it measures (stimulus), (b) what its specifications are, (c) what physical phenomenon it is sensitive to, (d) what conversion mechanism is employed, (e) what material it is fabricated from, (f) what is its field of application, and (g) the power requirements [5].

### 1.2.1.2 Actuators

Actuators are devices that accept a control command (mostly in the form of an electrical signal) and produce a change in the physical system by generating force, motion, heat, flow, and so forth. Normally, the actuators are used in conjunction with the power supply and a coupling mechanism as shown in Figure 1-3 [5].



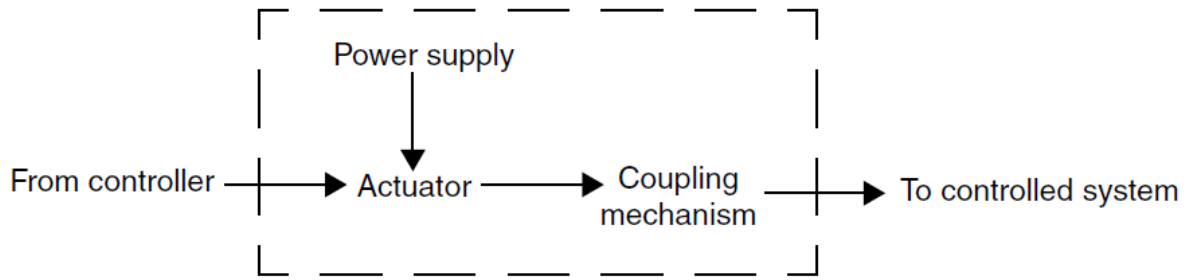


Figure 1-3: Schematic concept of an actuator [5].

### 1.3 Introduction to microfluidic

Microfluidics is regarded as a multidisciplinary technology that relates varied sciences involving chemistry, biochemistry, engineering, physics, micro/nano-technology and biotechnology. This field arrived in early 1980's and was exploited in many developments such as inkjet printing, microthermal technologies, and DNA chip. The large surface-to-volume ratio facilitates portability of microfluidic devices which is crucial for on-site testing [6,7]. Because of the scale-down effects, this technology offers many advantages like low consumption of specimens and reagents, low cost, high-throughput, rapid mass and heat transport, and accurate control of fluids at micro or nanoscale. The arrival of microfluidics technology gives exceptional opportunities in the fields of analytic and synthetic chemistry. Microfluidic reactor is an example of miniaturized device which designed precisely for chemistry synthesis, can simplify the synthesis process via specific control of reaction parameters and optimization of the production of the chemicals [8].

#### 1.3.1 What is microfluidics

Microfluidics is explained as the miniaturized systems that manipulate nanoliter to microliter fluids in channels with dimensions of tens to hundreds of micrometers [8]. The major operations performed by these systems are sample preparation, purification, separation, reaction, transport, immobilization, labeling, biosensing and detection. Fluid behavior at macro scale is completely distinct from micro and nano scale. For example, surface tension factor may become dominant in microfluidic devices [9].

### 1.3.2 Physical concept in microfluidics

Unlike solids, fluids are mainly characterized by molecules spaced with a large distance apart and hence have a large degree of freedom to move, and for gasses, which also are considered fluids, the molecules are spaced even further apart [10]. The definition of a fluid is “a material that deforms continuously under sheer stress” [11]. In fluid mechanics the fluid is described as a continuum, where the average fluid parameters are examined, rather than the individual molecule’s parameters of in the fluid. The continuum approximation states: “The macroscopic properties of the fluid are the same as if the fluid were perfectly continuous, instead of as in reality consisting of molecules” [11]. In microfluidics this statement holds most of the times as properties calculated are on the length scale of 10 or more micrometers; whereas the intermolecular properties are on the nanometer scale (intermolecular distance in fluids is ~0.3 nm) [10].

The most important parameters characterizing a liquid in static and dynamic are density ( $\rho$ ), pressure (P), and viscosity ( $\eta$ ). The density of a liquid is defined as mass (m) per unit volume (v) in units (kg/m<sup>3</sup>).

$$\rho = \frac{m}{v} \quad (1.1)$$

Pressure (P) is the ratio of force applied (F) to the area (A) over which that force is distributed in units kg/ms<sup>2</sup>, often referred to as Pascal (Pa).

$$dP = \frac{dF}{dA} \quad (1.2)$$

In microsystems filling height and reservoirs can be used to control the pressure and hence the flow rate in the system.

When you have a flow in a system, a resistance to the flow always exists. For liquids the flow resistance is mainly determined by the viscosity ( $\eta$ ) of the fluid, which in turn is determined by the ratio of the shear stress to the shear rate, in units of kg/ms or PaS. In more general terms the viscosity is given by

$$\eta = \frac{\text{constraint}}{\text{deformation}} = \frac{F/A}{dv/dl} \quad (1.3)$$

The above expression only holds for Newtonian liquids, i.e., where the viscosity does not depend on the fluid flow.<sup>1</sup> A value often used in microfluidics is the kinematic viscosity, which is the ratio of the viscosity and the density of the fluid, in unit m<sup>2</sup>/s

$$\nu = \frac{\eta}{\rho} \quad (1.4)$$

With the knowledge of these simple fluid parameters we can already yield some information about the flow in microsystems. If we take the ratio of the inertial forces to the viscous forces, we get a dimensionless number called the Reynolds number which can be used to define the type of flow expected in the system. The Reynolds number is given by

$$\text{Re} = \frac{\rho D v}{\eta} \quad (1.5)$$

In this equation D is the typical length scale in the system (typically the diameter for tubes or the smallest dimension, i.e., width or height, in rectangular channels), and v is the average velocity of the moving liquid. when Re>4000 turbulent flow occurs, and when Re<2300 laminar flow is dominant. Between 2300 and 4000 the so-called transitional flow, in general we can say that the flow is always laminar in microsystems.

in order to analyze the dynamics of fluid flow in microsystems we need a more in-depth approach and here the Navier–Stokes formalism needs to be introduced.

In fluid mechanics, the Navier-Stokes equations are nonlinear partial differential equations that describe the motion of Newtonian fluids, Navier–Stokes equation for incompressible fluids:

$$\rho(\partial_t v + v \cdot \nabla v) = -\nabla p + \eta \nabla^2 v \quad (1.6)$$

An incompressible fluid is a fluid with a density  $\rho$  that is constant in space and time, whereas a compressible fluid is a fluid with a density  $\rho$  that varies as a function of space and time. A parameter often used in microfluidics is the volumetric flow rate  $Q = \Delta V/t = \langle v \rangle A$ , where  $\langle v \rangle$  is the mean velocity and A is the crosssectional area. Given this equation this can be written as:

$$Q = \frac{\pi R^4}{8\eta L} \Delta P \quad (1.7)$$

The term  $8\eta L/\pi R^4$ , appearing as reciprocal in the above equation is called the hydraulic resistance ( $R_{Hyd}$ ). For a rectangular microfluidic channel, say a flat wide channel with height  $h$  and width  $w$ , where  $h/w \rightarrow 0$  the flow rate is given by

$$Q = \frac{h^2 w}{12\eta L} \Delta P \quad (1.8)$$

Rectangular channels are the most commonly used in microfabricated microfluidic systems due to the fabrication processes used [10].

## 1.4 Microfluidic Devices

### 1.4.1 Microfluidics systems

Microfluidic systems include the manipulation of fluids (liquids and gases) in channels with dimensions in the micrometer range ( $<1000 \mu\text{m}$ ). These systems, also indicated to as lab-on-chip or miniaturized total analysis systems ( $\mu\text{TAS}$ ), as well as their ability to streamline different processes with reduction in both time and cost. These systems provide high accuracy and reproducibility [12]. three types of microfluidics systems are distinguished: (1) continuous-flow; (2) droplet-based; and (3) digital microfluidics. Continuous microfluidic devices comprise of permanently etched microchannels and peripheral devices like micropumps and microvalves applied to manipulate a stream of fluid in these devices. Droplet-based microfluidic systems are depending on droplets creation in micro-channels utilizing two or more immiscible fluids at a T-junction. Digital microfluidic systems, are basically different, because they offer motion and control of discrete droplets on an array of planar electrostatically-actuated electrodes. Conventional microfluidic systems are based on the continuous flow regimes in micron-sized channels (Figure 1-4 a). which fabricated using soft-lithography methods. in order to decrease the sample consumption, and creating isolated reaction sites, droplet-based microfluidic systems have been evolved. The first generation of the droplet-based microfluidic systems utilized the continuous stream of two or more fluid mainly intersected at a T-junction to create discrete droplets which are isolated from each other using an immiscible fluid (Figure 1-4 b). To further reduce the volume consumption, digital microfluidic (DMF) was introduced in early 2000s. Rather than having continuous flow of droplets in the micro-channels, DMF systems create droplets on an array of electrostatically actuated electrodes (Figure 1-4 c) [6].

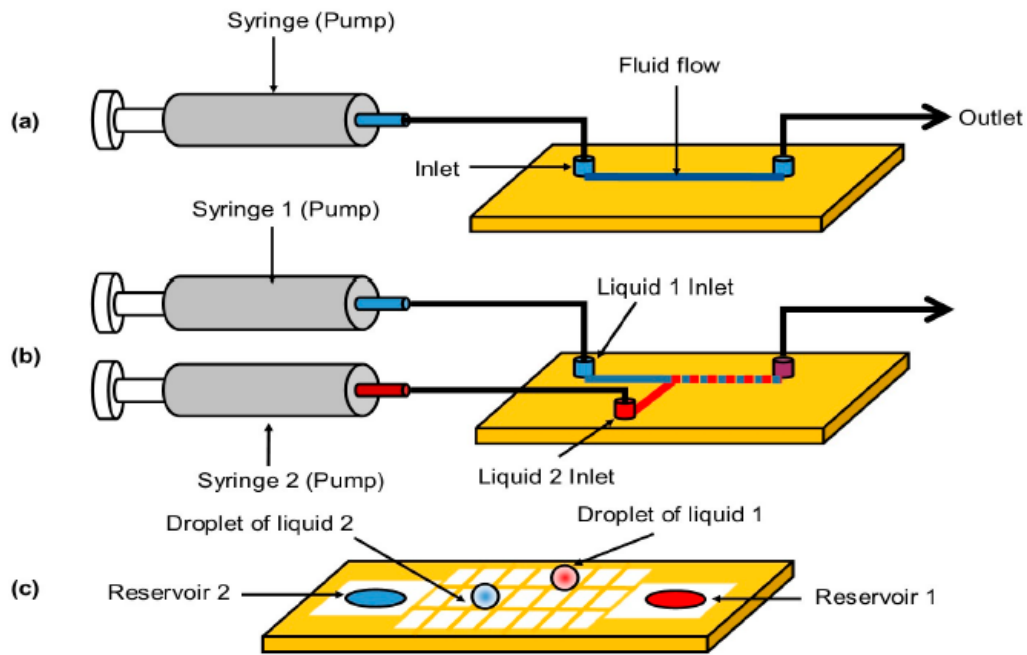


Figure 1-4: Schematic of the three microfluidic systems (a) continuous; (b) drop-based; and (c) digital [6].

Table 1-1 summarizes the operating and actuation methods and, advantages and disadvantages of the three different types of microfluidics [6].

Table 1-1: The comparison between the three types of microfluidics [6].

	Continuous-Flow Microfluidics	Droplet-Based Microfluidics	Digital Microfluidics
Operating Method	Motion of continuous fluid in micro-channels	Motion of droplets in micro-channels using streams of immiscible fluids	Motion of discrete droplets on an array of planar electrodes
Flow Actuation	Mechanical (syringe) pumps, Pneumatic pressure, Electrokinetic	Mechanical (syringe) pumps, Pneumatic pressure	Electrowetting On Dielectric, Dielectrophoresis
Advantages	Ease of fabrication and operation, suitable for applications that require a continuous flow with relatively high sampling volume, and being compatible with most of current screening and sensing mechanisms	Ease of fabrication and operation, suitable for a applications that require isolated reaction sites to avoid cross contamination	Lower sample consumption, scalability, better localization, reconfigurability, and portability
Disadvantages	High sample volume consumption compared to other microfluidic systems, possible contamination, and not being scalable due to fabrication and physical limitations	No control over individual droplets, challenging to create droplets of different sizes using the same setup, and challenging to implement stable gas-liquid systems	Complicated fabrication procedure, and bio-adsorption and evaporation

## 1.4.2 Micropumps

Most pumps use a diaphragm or a flexible membrane. Displacement of the diaphragm applies a force to the fluid, thus causing it to be displaced [13]. Materials for the diaphragms include thin silicon, glass films, elastomeric polymers such as thin layers of silicone or polydimethylsiloxane (PDMS), and thin films of other polymers such as polyimide and parylene C [13]. Such pumps normally have passive valves that regulate the flow of fluid into and out of the pump chambers. During a single pump cycle, movement of the diaphragm first increases the volume of the pump chamber (during the suction or expansion stroke), thereby drawing fluid into the chamber. A subsequent decrease in the volume of the pump chamber during the alternate stroke of the diaphragm (during the contraction or discharge stroke) forces the fluid out (Figure 1-5) [13].

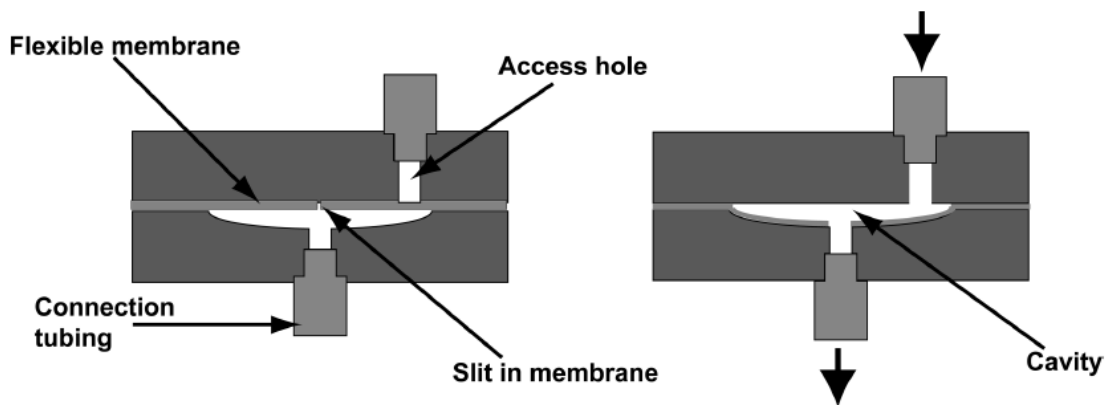


Figure 1-5: Schematic showing the mode of operation of a passive membrane type valve [13].

Alternatively, electrostatically driven micropumps can be driven by both AC and DC current. Materials include multilayer parylene technology [14], and a combination of glass, silicon, and polysilicon with gold electrodes [15].

Piezoelectrically driven micropumps have become more common because they are relatively inexpensive to fabricate especially when the diaphragm or flexible membrane is made with cheap elastomeric materials like PDMS instead of thin glass or silicon membranes. The literature on piezoelectric-driven micropumps is extensive, with many recent designs reported in the literature [16,17].

Thermally actuated micropumps depend on expansion of materials or changes in stress due to applied heat for actuation. A thermopneumatic-actuated

polydimethylsiloxane (PDMS)-based micropump has been fabricated and its properties have been characterized by Kim et al [18].

Shin et al used thin film (10  $\mu\text{m}$ ) nickel–titanium (NiTi) shape memory alloy (SMA) to develop a compact actuator pump generating high output force at large velocities [19]. Drawbacks for such systems include slow response times and low pumping rates.

Electromagnetically driven micropumps use Lorentz forces generated by interaction of electromagnetic fields (when an electric current is passed through a coil that surrounds a permanent magnet). The electromagnet is designed with a movable part that deflects an attached membrane upon turning on the electromagnet. The advantage of this actuation mechanism over others (such as electrostatic) is a lower requirement of voltage [13]. Furthermore, by incorporating the coils and permanent magnet directly into the device, electromagnetically driven micropumps have been fabricated with improved diaphragm deflection and reduced sizes [20,21]. Modifications to this technique include the use of composite diaphragms in which magnetic material is incorporated into the diaphragm material such as PDMS [22].

### **1.4.3 Microvalve**

Fluid control is often one of the most important elements for the realization of a fully integrated microfluidic system. In pressure driven systems, microvalves (i.e., small valves that are built into the chip itself) can switch and regulate flow, as well as physically isolate different parts of a microfluidic system. Microvalves can generally be classified into two main categories: active and passive [13]. The valves can be designed to be normally open, closed, or bistable (in which case the resting state can be adjusted) [13].

#### **1.4.3.1 Active Microvalves**

Actively driven mechanical microvalves are designed based on a number of different actuation mechanisms. In many designs, a membrane is deflected when the actuating source is turned on [13].

Magnetically actuated microvalves can use permanent magnets [23], electromagnets, or a hybrid attached to a membrane. Instead of using membranes, valves using magnetic balls have also been reported, such as a design with three polymer layers that form the base and casing for the valve and where the fluidic layer is made of

metal[24]. Other designs of magnetically actuated ball valves can be scaled down to the nanometer length scale, which is important for nanofluidic applications [25].

Electrostatically actuated microvalves have also been built. Because of high voltage requirements, however, this type of valve is often used to control gas flow rather than liquids (which can undergo electrolysis at high voltages). Electrokinetics has been used to move particles and liquids in microfluidics and has also been used for fluid switching and control. For example, Kirby et al present a microchip-based, voltage-addressable on/ off valve architecture that is fundamentally consistent with the pressures and solvents employed for high-pressure liquid chromatography [26].

Piezoelectric-driven microvalves are quite common. Although piezoelectric disks are able to generate appreciable deflection forces, their stroke is limited due to the high Young's modulus of the materials used. This limitation has been addressed by a number of groups using the hydraulic amplification principle [27,28].

#### 1.4.3.2 Passive microvalves

Passive mechanical valves are normally flaps, spherical balls, membranes with slits, or other mobile structures that are displaced by motion of the fluid due to forward pressure. Figure 1-6 shows the general mode of operation of the membrane type with a slit. These types of valves can also act as check valves [13].

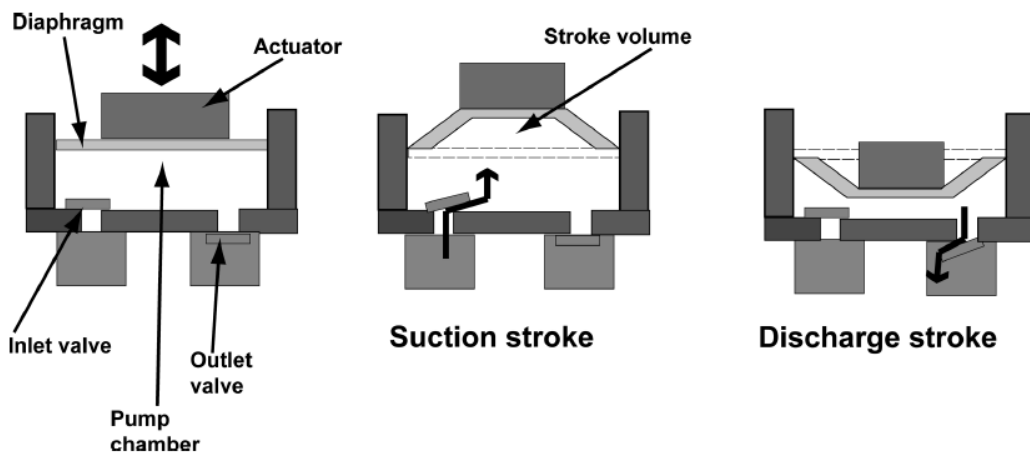


Figure 1-6: Schematic showing the mode of operation of mechanical displacement pumps [13].



## 1.5 Materials and Fabrication methods

Fabrication and designing of microfluidics platforms for biosensors require careful addressing and considerations such as: dimensions, materials, and the process used for fabrication to enhance the biocompatibility and wet ability of the manufactured device. Glass and silicon are the most common materials used to fabricate and design microfluidic platforms. Due to both their low cost and production of polymer materials. The great chemical, physical and mechanical properties of polymers such as polymethyl methacrylate (PMMA), and polydimethylsiloxane (PDMS) have raised the biocompatibility of using them in the manufacturing and designing of microfluidic devices. Examples of some of the different fabrication processes and materials used in fabrication of microfluidic devices for biosensing applications are shown in Table 1-2 [6]. On the other side, Three-dimensional printing, or additive manufacturing, is considered as a new technique to manufacture microfluidic devices. It provides simplicity, a large variety of materials, and automated manufacturing. As opposed to other microfluidic manufacturing methods, as well as offering true 3-D digital design capability and producing a fully integrated microfluidic device in a single process. In order to produce a micropattern, Three-dimensional printing does not depend on masks or molds; it only requires input from a CAD software to be able to provide a geometrically precise 3-D structure [12].

Table 1-2: Examples of some of the different fabrication methods and materials used to fabricate microfluidic devices for biosensing applications [6].

Fabrication Method	Fabrication Material	Advantages	Disadvantages
Photolithography	PDMS	Protability Cost-effective and high automation High sensitivity	Low throughput
Soft lithography	PDMS	Real-time detection Portable Disposable Cost-effective	Requiring high sample concentration
Nano-printing	PMMA	Cost-effective High sensitivity	Expensive Low throughput

## **1.6 Application of microfluidics**

Microfluidics has found applications in a wide range of fields. For example, in chemistry, employing microfluidics enhances material synthesis, particularly nanomaterials and nanostructures due to the interface between the reagents is larger comparative to their volume in biology, microfluidics has been used for molecular analysis, cell analysis, and cell sorting. In drug delivery, neural probes and implantable devices have combined microfluidic components that can correctly deliver small amounts of medicine into special targets inside the body. In electronics, microfluidics has been utilized as sensors, specifically for wearable systems [29].

### **1.6.1 Microfluidic chip, LOC and ITAS devices**

Microfluidic chips effectuate the interconnection through microfluidic channels. Utilizing microfabrication processes, their geometry and dimensions can be specifically defined and fabricated. Miniaturization provides a substantial reduction in liquid volume and the amount of substance required. meanwhile, the fluidic layout can only be modified through chip redesign and refabrication, which take time and can be costly. Once the design has been defined, many chips can be manufactured with great reproducibility [30]. They also can give different unit operation from mixing to filtration and analysis [12]. A lab-on-a-chip (LOC) or miniaturized analysis systems is a device that offers one or several laboratory functions on a single chip from square millimeters to a few square centimeters in size [31,32], while “Micro Total Analysis Systems ( $\mu$ TAS)” includes the integration of the entire sequence of lab processes required for a single chemical analysis. when it became apparent that  $\mu$ TAS technologies can possess broader applicability. With the growing interest in device miniaturization, lab-on-a chip (LOC) techniques have been developed as miniaturized platforms for application in various fields of research, such as analytical chemistry, biochemical assays, and environmental tests [33]. Various application of LOC are showed in Figure 1-7 like mixing, separation, and detection.

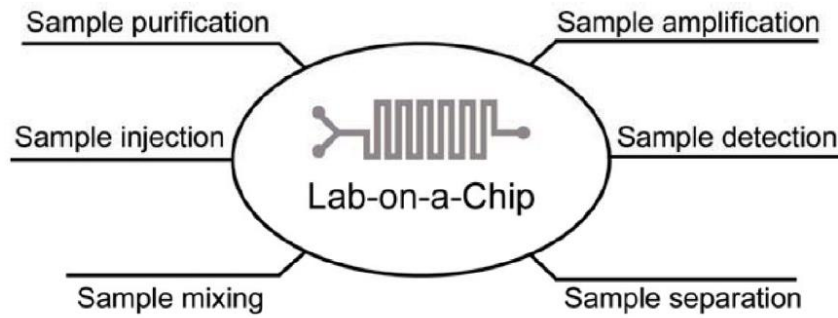


Figure 1-7: Unit components making up the lab-on-a-chip (LOC) system [33].

The benefits of microfluidics and disadvantage of LOC are resumed in table 1-3 [7].

Table 1-3: Benefits and disadvantage of LOC [7].

Advantages	Disadvantages
- reduced fluid volumes consumption	- The dominance of some chemical and physical effects on small scale
- Shorter times for analysis	- The principles of detection may not always fit to reduce sizes in a favorable way
- faster responses	- The geometric precision not comparable to precision engineering.
- Better control of processes	- LOC remains a novel technology that is not yet fully developed
- Lower fabrication costs	

The integration of pumps into microfluidic chips mostly relies on peristaltic pumping technology [34]. The main advantages of such systems are a reduction in the overall liquid volume, compactness, and the fact that the liquid does not leave the chip. Implementation is generally realized through serial arrangements of pumping chambers and valves that contain elastic membranes [30]. Figure 1-8 provides a functional diagram of LOCs.

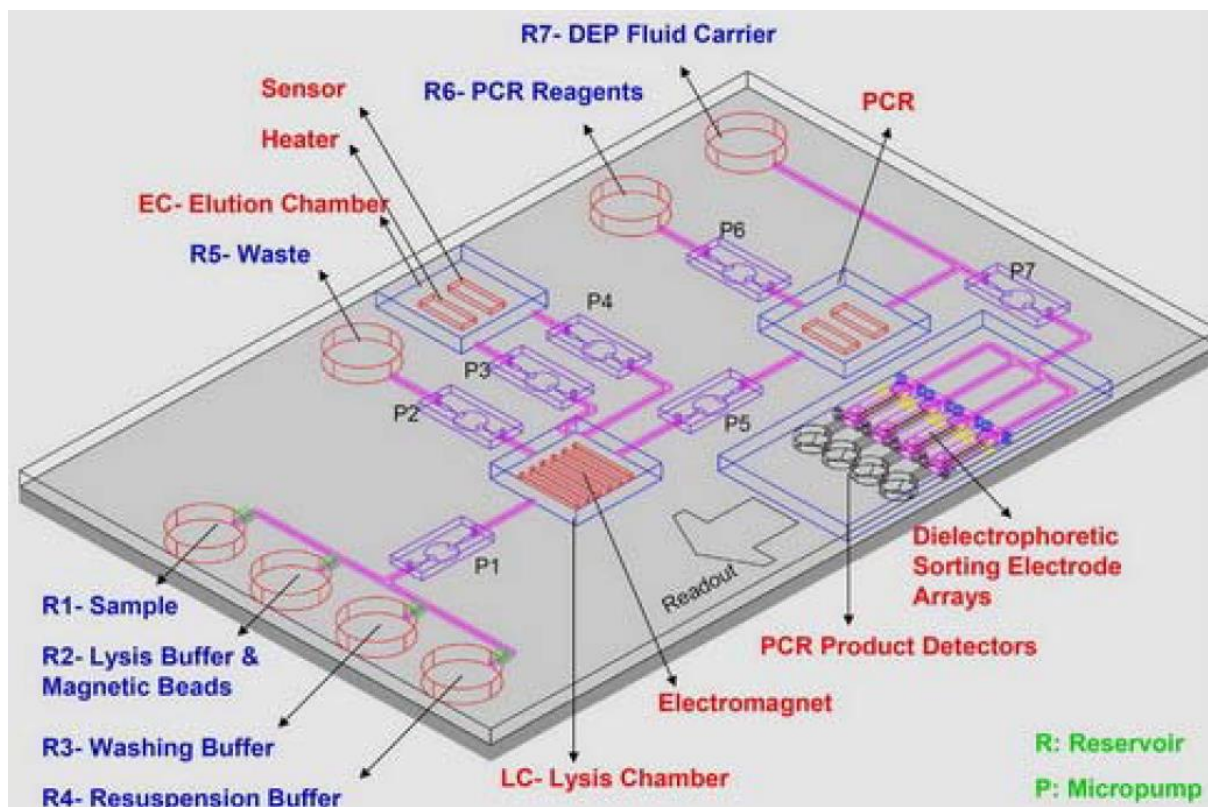


Figure 1-8: A Lab-on-a-Chip [35].

## 1.7 Membrane

Membranes are represented as a porous or dense barrier that permits the flow of certain compounds selectively in a fluid. The passage of molecules through a membrane barrier is driven by a diversity of forces like concentration gradient, pressure difference, thermal variation, electrical force and so on. this technology has been broadly used in chemical industry and biological engineering, exhibiting a lot of inherent benefits involving cost-effective, operation-convenient, function-versatile and environment-compatible related with ordinary separation methods [36]. Combining membranes with microfluidics can magnify their benefits to provide more beneficial applications such as size selective DNA transport through a nanoporous membrane in a polydimethylsiloxane (PDMS) microfluidic device, photosensitive thermoset termed OSTEMER 322-40 as a complementary substance to readily manufacture complex multi-layered microdevices for uses in life science, and robust preparation technology for free standing porous cyclic olefin copolymer membranes applied for micro engineered in-vitro models of tissues and organs [36]. The success of the micromechanical actuators requires good performance of membranes. As active valves and pumps, for instance, membranes of large deflection can be utilized to

transform pressure into displacement. Knowing deflection-pressure relationship is important in order to typify the behavior of the actuator. For small deflections, the dependence between pressure and deflection is linear [37].

### 1.7.1 Theoretical basis of membrane technology

The magnitude of acting force can be expressed as the ratio of the potential difference on both sides of the membrane and membrane thickness.

$$F = \frac{\Delta X}{l} \quad (1.10)$$

Where,  $F$  is acting force,  $\Delta X$  is potential difference and  $l$  is thickness of membrane. The potential difference can be diverse such as chemical, electrokinetical, magnetometric, Centrifugal, gravitational, and so on.

The flux can be given as follow:

$$J = A \times F \quad (1.11)$$

Where,  $J$  is the flux in steady state, when given force  $F$  is applied to components,  $A$  represents the resistance of membrane as a dispersion medium. To a mixture, the selectivity of membrane can be expressed with retention rate  $R$  or separation factor  $\alpha$ . It is convenient to define selectivity with retention rate  $R$  of solute for dilute solution. Some of the solute is trapped off, and the solvent molecules can dropping freely through the membrane. Retention rate  $R$  is expressed as:

$$R = \frac{c_f - c_p}{c_f} = 1 - \frac{c_p}{c_f} \quad (1.12)$$

Where,  $c_f$  is solute concentration of the origin solution and  $c_p$  is solute concentration of the penetration.  $R$  that is unrelated to unit of the concentration is dimensionless number.  $R$  can vary from 100% (solute is held back totally, ideal semi-permeable membrane) to 0% (solute passage can be freely through membrane). It is appropriate to represent selectivity with separation factor  $\alpha$  for a gas mixture or the organic liquid mixture. For a combination containing component A and component B, separation factor  $\alpha_{A/B}$  is represented as:

$$\alpha_{A/B} = \frac{y_A/y_B}{x_A/x_B} \quad (1.13)$$

Where,  $y_A$  and  $y_B$  are concentration of component A and component B in the penetration respectively;  $x_A$  and  $x_B$  is concentration of component A and component B in the origin solution [36].

**CHAPTER 2:  
INTRODUCTION TO  
MAGNETIC POLYMER  
COMPOSITE**

## **2.1 Introduction**

In the fabrication of miniaturized mechanical components for MEMS and lab-on-a-chip systems, polymeric materials have attracted a great deal of attention, as they are lightweight, flexible and easily processed. Various engineered polymeric materials, such as electroactive polymers, carbon nanotube composites and liquid crystal polymers, are currently under investigation for implementation [38]. Composites with magnetic fillers dispersed in a polymer matrix represent a system with physical and chemical properties that are influenced by the ferrite powder fillers and polymer matrix characteristics as well as by the interaction at the ferrite-polymer interface [39]. In this chapter we start with introducing polymers and polymer composites, focusing on their main properties. Then, explain the magnetic nanoparticles concept and how important they are once they filled within these composites showing significant new properties. And finally, we end up with basics concepts in magnetism like magnetic dipole moment, magnetic fields, magnetic material types.

## **2.2 Polymer**

### **2.2.1 Introduction**

The word Polymer originates from the Greek word "polymeros" which means many-membered, (Clegg and Collyer 1993). Often the word polymer is thought of as being composed of the two words; "poly" meaning many and "mer" meaning unit. Thus, the word polymer means many units and is very descriptive of a polymer molecule [40].

Polymers have been widely used in MEMS/microfluidic devices primarily due their low cost, chemical inertness, low electrical and thermal conductivities, ease of surface modification, and their biocompatibility [5].

A wide variety of polymers have been used in fabrication of microsystems for biomedical applications. They include thermoplastic materials such as polymethyl methacrylate, polycarbonate, polyvinylidene fluoride, polysulfone, polystyrene, polyvinylchloride, polypropylene, polyetheretherketone, polyoxymethylene, and polyamid [41], as well as cross-linked materials such as PDMS, paraxylylene (parylene), SU-8, hydrogels, porous polymers, biodegradable polymers, polyesters, polyimide (PI), and paraffin [5].

## **2.2.2 Proprieties**

Polymers are an increasingly important MEMS material. They are available in diverse forms and possess material properties not found in more traditional microfabrication materials originating from the integrated circuit industry. These include, for example, improved fracture strength, low Young's modulus, and high elongation. Many polymers also exhibit biocompatibility and chemical inertness which are desirable in challenging biological or chemical applications. Furthermore, low material and processing costs present interesting possibilities in MEMS both in terms of fabrication of novel research devices and mass production of inexpensive products. A variety of traditional and nontraditional processing approaches exists to manipulate polymeric materials as substrates, coatings, and sacrificial or structural layers in MEMS devices. A wide variety of polymer types and classifications exists (e.g., elastomers, epoxies, conductive polymers, hydrogels, thermosets, thermoplastics, etc.) ; it is the combination of material properties, processing conditions, and intended use (e.g., substrate, coating, sacrificial layer, or structural layer) that govern the selection of appropriate polymer type for a particular application.

### **2.2.2.1 Classification of polymer**

Most polymers can be broadly classified as either thermoplastics or thermosets. The fundamental physical difference between the two has to do with the bonding between molecular chains - thermoplastics have only secondary bonds between chains, while thermosets also have primary bonds between chains. The names are not only associated with the chemical structure of each but their general thermal and processing characteristics as well since this basic structural difference greatly impacts material properties. Thermoplastic polymers can be melted or molded while thermosetting polymers cannot be melted or molded in the general sense of the term. Thermoplastic or thermosetting polymers are sometimes identified by other names such as "linear" and "cross-linked" respectively. It should be noted that the term linear here applies to molecular structure and not to mechanical (stress-strain) characteristics [40].



### 2.2.2.2 Mechanical proprieties

In this section, we would Highlight some fundamental mechanical properties of the material in particular polymer mechanical Properties. Several mechanical characteristics can be distinguished:

- **strength:** it is the stress that needs to fracture the specimen, it can be appear in different form Like (tensile, compressional, flexural, and torsional, etc), In case of increasing strength, polymers follow the next order: linear<br>branched <crosslinked <network. To describe the dependence of molecular weight on the tensile strength, the following expression was considered:

$$\sigma = \sigma_{\infty} - \frac{A}{M} \quad (2.1)$$

Where  $\sigma_{\infty}$ : is the tensile strength of polymer with molecular weight of infinity ,A is some constant and M is the molecular weight [42].

Cross-linking and crystallinity factors are both responsible for the growth of the strength. the first factor confines the motion of chains and the second affects strength due to the intermolecular bonding is more important in the crystalline phase [42].

- **Percent Elongation to break**

It is the strain in the material on its rupture, as shown in Figure 2-1 a, it uses for measuring the ductility and the percentage change in the length of the material before breakage [42].

- **Young's Modulus** (modulus of elasticity or tensile Modulus):

It represents the ratio of stress to the strain in the linearly elastic region, the elastic modulus is a measure of the stiffness of the material [42].

$$E = \frac{\text{Tensile Stress}(\sigma)}{\text{Tensile Strain}(\varepsilon)} \quad (2.2)$$

- **Toughness:** it is represented by the area under stress-strain curve (Figure 2-1 a). also, it measures the absorbed energy by the material before breakage.

$$\text{Toughness} = \int \sigma d\varepsilon \quad (2.3)$$

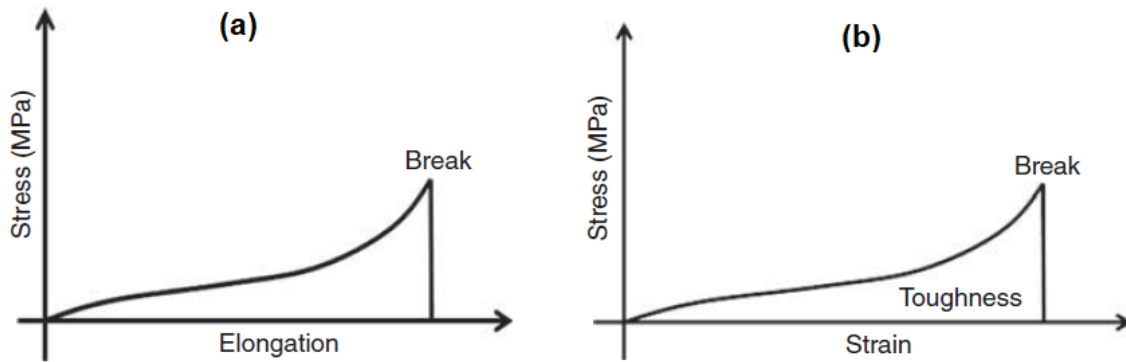


Figure 2-1: (a) Elongation to break of the polymer (b) The toughness of polymer material [42].

The curve in Figure 2-2 shows stress-strain behavior of different type of materials. the rigid materials have high young's modulus like brittle polymers. Also, ductile polymers have analogous Tensile Modulus, but with higher breakage toughness. otherwise, elastomers possess low elastic modulus and are rubbery in natural state [42].

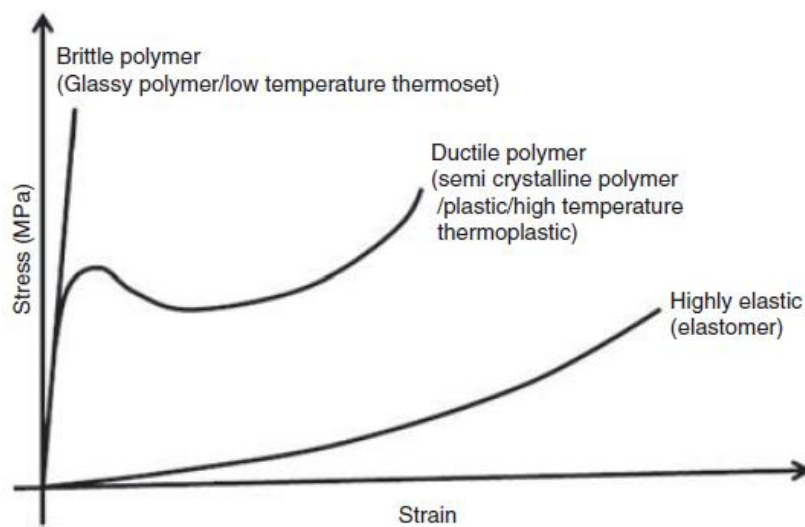


Figure 2-2: Stress–strain behavior of different types of materials [42].

Figure 2-3 show Stress-strain dependence while the change of temperature. It is noticed that the elastic modulus and Tensile strength are inversely proportional to the temperature, whereas the ductility is improved [42].

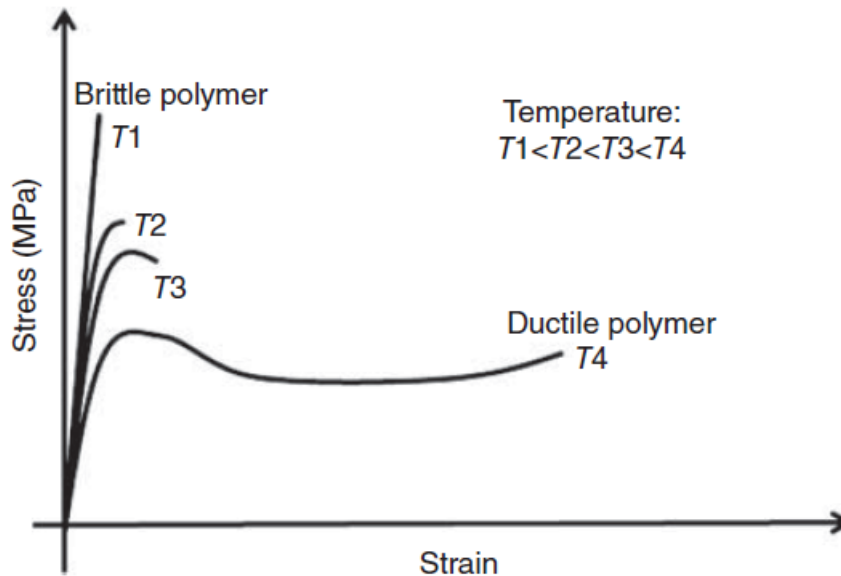


Figure 2-3: Effect of temperature on the mechanical properties of polymer [42].

- **Viscoelasticity**

Typically, the deformation can be classified in two kinds elastic and viscous depending on the temperature and strain rate. At low temperature and high strain rate elastic behavior is observed. Whereas, in the viscous behavior the temperature is high and strain rate is low. At intermediate values of temperature and strain rate the behavior is called viscoelasticity [42].

### 2.2.2.3 Optical properties

Two classes of optical appearance features can be identified: Those related with the volume (bulk) which are characterized by color and transparency. whether in natural polymer or modified by adding additives. Most polymer are colorless in visible light and demonstrate many properties from glass clarity to full opaqueness. Further, the surface properties may change from high gloss to full dullness. Also, they show no specific absorption in the visible light. whereas, they possess particular absorption bands in the infrared region of spectrum. Furthermore, the phenomenon of birefringence occurs in polymer melts under forced flow (shear, elongational, stresses) or under tension, and in solid polymer after stretch orientation; the oriented polymer is cooled to below its glass transition temperature before the molecules have had a chance to relax to their random coiled configuration [43].

Generally, amorphous polymers are transparent, but in case of adding fillers, they become opaque. whereas, crystalline polymers are translucent or opaque. The refractive index, light transmission and dispersive properties of several polymers are given in the Table 2-1 [40].

Table 2-1: Typical optical properties [40].

<b>Material</b>	<b>Refractive Index</b>	<b>Light Transmission</b>
<b>Acrylic</b>	1.49	92
<b>Polycarbonate</b>	1.59	89
<b>Polystyrene</b>	1.57	88
<b>PMMA</b>	1.49	-
<b>Glass</b>	1.5	-

### 2.2.3 Application

One of the first uses for polymeric materials was for the insulation of electrical cables for power lines. Also, Fiber reinforced plastics (FRP) or polymer matrix composites (PMC) are now often used in automotive, aerospace, boating, and other applications. In addition, almost all adhesives are polymers and are used broadly to connect structural components. amorphous thermoplastic polymers are commonly used in optical applications, such as lenses for enhancing vision [40].

On the other hand, Polymers Have played an essential role in advancing MEMS into new applications, particularly in the area of biomedical MEMS (or bioMEMS). For example, SU-8 has been used to design microfluidic channels for LOC devices, as well as waveguides, mirrors, cladding for optical applications and microneedles for drug delivery devices. One more example of polymers uses is micromachined polyimide, with a specific focus on electronic neuroprosthetic devices built on the flexible substrate for improved *in vivo* performance [44].

### 2.3 Polymer Composite

By definition, polymer composites consist of a base polymer and a dispersed phase, showing properties that differ from those of the individual constituents, generally, these phases are some kind of particle in size range of nanometer or micrometer. These composites can be micropatterned utilizing typical microfabrication methods for instance micro molding, screen, inkjet printing, and photolithography, that remain compatible with the undoped base polymer. In all actuation approaches based on

polymer composites introduced so far, one kind of particle has been dispersed. However, the creation of composites containing of more than two phases, leading to materials that are responsive to multiple stimuli, would simplify the realization of complex actuation schemes [45]. One way to categorize polymer composites is by the features of the fibers used: (a) discontinuous, lower performance, (b) continuous, moderate performance, and (c) continuous, high performance. demonstrations of each are (a) sheet molding compound (SMC) and injectionmolded thermoplastics, that reinforced with discontinuous glass fibers; (b) glass filament wound pipe and pressure vessels for the chemical handling industry; and (c) graphite fiber reinforced, multi-ply laminates applied in aircraft structures [46].

## 2.4 Magnetic polymer composite

Magnetic polymer composites consist of a base polymer and a dispersed magnetic phase, generally, solid particles in the size range of nanometers to micrometers and with particular magnetic properties. They have proved to be functional in the realization of microfluidic actuators. depending on chemical composition, crystalline structure and

Table 2-2 overview on magnetic polymer composite

Source	Polymer	Nanoparticule	Size of MNP	Thickness of the membrane	Dimension
Marchi 2015 [47]	silicon elastomer Ecoflex 10	ferromagnetic particles based on a Nd <sub>2</sub> Fe <sub>14</sub> B	10.5µm	400µm	About 10 mm
Akeem Cruickshank master 2014 [48]	Sylgard 184 PDMS	Fe <sub>2</sub> O <sub>3</sub> Paramagnetic	24.6nm	around 100-200 µm,	1.3 × 1.3 cm
F. Fahrni 2009 [49]	PDMS	Fe <sub>2</sub> O <sub>3</sub> Paramagnetic	10nm	300µm	5 mm diameter
Fatemeh(Nazly) Pirmoradi 2009 [50]	PDMS	Fe <sub>3</sub> O <sub>4</sub> Fe <sub>2</sub> O <sub>3</sub>	20-30 nm	50µm	600 µm × 450 µm
Lin Zhu, 2013 [51]	PDMS	nickel particles nickel fibers	3–5 µm	-	--

size of the particles used, the adjustable magnetic properties can be diamagnetic, paramagnetic, superparamagnetic and ferromagnetic, the best prominent candidates are neodymium ( $\text{Nd}_2\text{Fe}_{14}\text{B}$ ) and iron (III) oxide ( $\text{Fe}_2\text{O}_3$ ). A review has exhibited that PDMS is the most common base polymer for producing magnetic composites, and that in most of the cases composite membranes or cilium-like structures actuated with electromagnets are employed for fluid transport and mixing [45]. Table 2-2 give an overview about magnetic polymer composite in the literature.

## **2.5 What is a magnetic nanoparticle?**

Nanoparticles (NPs) are ultrafine particles in nanometer range, offering high surface area- to-volume ratio and are thus extremely reactive, versatile, and strong as compared to the bulk ones. These features confer unbounded possibilities for enhancing the unique mechanical, optical, and magnetic NPs properties. NPs are categorized into either organic group, consisting of carbon nanotubes, liposomes, and fullerenes, or inorganic group, including quantum dots and magnetic nanoparticles (MNPs). MNPs have the capability of being functionalized at both cellular and molecular levels. They are zero-dimensional materials with metal-based configuration. These NPs have gained increased importance because they can be easily manipulated using alternating current magnetic field (ACMF) and subsequently employed in various applications. Nanometer-sized MNPs show unique properties, such as high saturation magnetization ( $M_s$ ), biocompatibility, and less toxicity; these particles feature easy controllability, biological compatibility, physicochemical properties, and superior magnetic properties [52].

### **2.5.1 Types of Magnetic Nanoparticles and Applications**

Among Different types of magnetic particles, including iron oxide, nickel, and cobalt, iron oxide ( $\text{Fe}_3\text{O}_4$  or  $\text{Fe}_2\text{O}_3$ ) particles have fascinated more research attention [8]. Magnetic particles can be applied to selectively attach, manipulate or transport targeted species to a desired position under the magnetic field effect. Due to their size, magnetic nanoparticles are superparamagnetic, presenting great potential in a variety of applications in their bare form or through coating with a surface coating and functional group chosen for a specific application, as densmetric separation in magnetic liquids, therapeutic, diagnostic testing, effluent processing, and metal ion removal [53]. also, in ferrofluids, refrigeration systems, medical imaging, drug

targeting, and catalysis [54]. in the field of biotechnology, such as DNA and RNA separation, cell separation, drug delivery system DDS, magnetic resonance imaging MRI, and hyperthermia [55].

## **2.6 Basic concept of magnetic**

### **2.6.1 Introduction**

Magnetism is a striking physical phenomenon and has captivated humanity since its discovery. Its service in applications has impacted and been valuable to, arguably, all facets of our society to date. For the vast period of time that we have used magnetic phenomena, the employment has been macroscopic, at least down to bulk engineering dimensions. However, the last two decades have seen the evolution of its implementation and the use in an entire host of sub-microscale notions, devices, and applications [56].

The magnetic effects can be created by a magnet or by current carrying conductor. The area around one of them, is named as magnetic field. A charge moving in a magnetic field experiences a deflecting force. If a charge moving through a point experiences a deflecting force, then a magnetic field is said to exist at that point. This field is represented by a vector quantity  $B$ , termed magnetic field or magnetic induction. That is placed normal to the lines measures the magnitude of magnetic induction or magnetic flux density  $B$ . obviously, in an area is the relative spacing of the lines of inductions, the greater is the magnetic induction. The tangent to the line of induction at any point gives the direction of magnetic induction  $B$  at that point. The induction lines simply represent graphically how  $B$  varies throughout a certain region of space. In this section we would highlight some of the magnetism theories such as magnetic fields, and electromagnetic force [57].

### **2.6.2 The magnetic dipole moment**

The fundamental quantity in solid-state magnetism is the magnetic moment  $m$ . On an atomic scale, intrinsic magnetic moments are related with the spin of each electron and a further contribution is related with its orbital motion around the nucleus. Most of the spin and orbital moments of the atomic electrons manage to cancel out, and only a few transition metal atoms or ions retain a resultant moment on the atomic scale in solids.

According to Ampère, a magnet is similar to a circulating electric current; the magnetic moment  $m$  can be described by a tiny current loop (see Figure 2-4). If the loop area is  $A$  square meters, and the flowing current is  $I$  amperes, then  $m = I \cdot A$  [58].

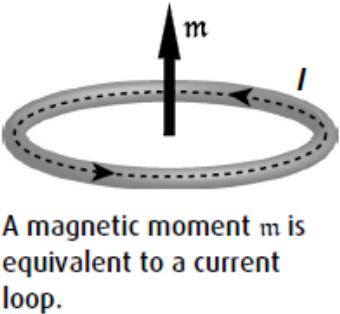


Figure 2-4: magnetic moment and current [58].

**2.6.3 Magnetic fields**

To describe magnetic fields two fields are introduced the magnetic field strength  $H$  or magnetizing force. And the magnetic flux density or induction  $B$ . Both fields are closely related. In SI units, 1 A/m (ampere per meter) and 1 T (Tesla) are used for  $H$  and  $B$ , respectively. In vacuum the following relation holds:

$$\vec{B} = \mu_0 \cdot \vec{H} \tag{2.4}$$

In matter the relation becomes:

$$\vec{B} = \mu_0 \cdot (\vec{H} + \vec{M}) = \mu \mu_0 \cdot \vec{H} \tag{2.5}$$

Where:

$$\vec{M} = (\mu - 1) \cdot \vec{H} = \chi \cdot \vec{H} \tag{2.6}$$

$\vec{M}$  is the magnetization of the material (which specifies the magnetic dipole moment per unit volume),  $\mu$  its relative magnetic permeability and  $\chi$  is magnetic susceptibility. In general, and in particular for crystalline solids,  $\mu$  and  $\chi$  are tensors, but for isotropic materials, where  $\vec{M}$  is parallel to  $\vec{B}$ , both constants become scalars [59,60].

**2.6.4 Magnetic flux and flux density**

Magnetic flux is the amount of magnetic field (or the number of lines of force) produced by a magnetic source. Which is symbolized by  $\Phi$ . The unit of magnetic flux is the weber; Wb.



Magnetic flux density is the amount of flux passing through a defined area that is perpendicular to the direction of the flux is given In tesla by:

$$B = \frac{\Phi}{A} \quad (2.7)$$

Where A(m<sup>2</sup>) is the area, and B is the magnetic flux density. where 1T = 1 Wb/m<sup>2</sup> [61].

### 2.6.5 Magnetic susceptibility and permeability

Permeability, defined as  $\mu = B / H$ , is a common measure for describing how a given material amplifies or reduces an externally applied field H.

In a large class of materials, there exists an approximately linear relationship between M and H. If the material is isotropic then  $M = \chi H$ ,

Where the dimensionless quantity  $\chi$  is known as the magnetic susceptibility. If  $\chi$  is positive then the material is called paramagnetic, and the magnetic field is strengthened by the presence of the material. If  $\chi$  is negative then the material is called diamagnetic, and the magnetic field is weakened in the presence of the material. The magnetic susceptibilities of paramagnetic and diamagnetic materials are generally extremely small [56,60].

### 2.6.6 Electromagnetic force

Charged particles can be influenced by both electric and magnetic forces. The difference between them is that for a magnetic force to act the charge must be moving. Whereas, the electric force is independent of motion. Due to the combination of these two forces, a total force will appear which called electromagnetic force.

If a charge q is at a point where electric field is E, the electric force  $F_e$  is given by:

$$\vec{F}_e = q\vec{E} \quad (2.8)$$

Let consider a charge particle q which is moving with velocity  $\vec{v}$  in magnetic field  $\vec{B}$ , then the magnetic force acting on that particle is given by:

$$\vec{F}_m = q(\vec{v} \times \vec{B}) \quad (2.9)$$

When the electric force is added to a magnetic force  $F_m$ . We have the total electromagnetic force on the particle, which is known as the Lorentz force law [57].

$$\vec{F} = \vec{F}_e + \vec{F}_m = q(\vec{E} + \vec{v} \times \vec{B}) \quad (2.10)$$

### 2.6.7 Magnetization

The volume magnetization  $M$  equals the vector sum of all the magnetic moments ( $\mu_i$ ) per cubic meter ( $V$ ). Magnetic moments appear from flowing currents (either quantum or free currents) and are equal to the product of the current in the loop times the loop's area; moments have units of amp-meter<sup>2</sup> ( $A\ m^2$ ). The moment is normal to the plane of the loop and in the direction such that the H-field created by the current passes through the loop according to the right-hand rule.

$$M = \frac{(\sum_i \mu_i)}{V} \quad [A\ m^{-1}] \quad (2.11)$$

## 2.7 Type of magnetic material

All materials can be classified in terms of their magnetic behavior in response to magnetic fields. Three main classes of magnetism have been discussed. These types of magnetism are: ferromagnetism, Paramagnetic, and diamagnetism.

### 2.7.1 Diamagnetic material

Diamagnetic materials are those which are repelled by magnets and when placed in magnetic field move from stronger to weaker part of the field. Some examples of these materials are: bismuth phosphorus Antimony and copper. When a diamagnetic substance is placed in a magnetic field, it sets itself at right angles to the direction of the force lines which go away from the material. Diamagnetic materials magnetize in proportion to the field in which they are placed, following the opposite direction, with low ratio of the object magnetization to the field producing [62]. The magnetization of the diamagnetic material is shown in Figure 2-5

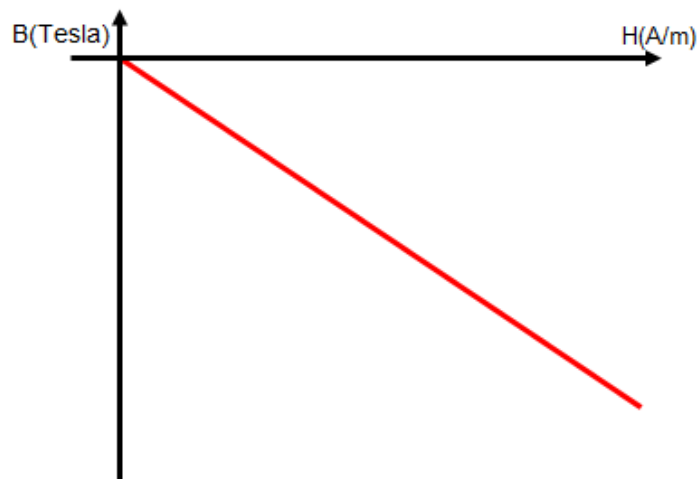


Figure 2-5: Magnetization of a diamagnetic material.

**2.7.2 Paramagnetic material**

Paramagnetic materials are those which are attracted by magnets and when placed in a magnetic field they turn from weaker to stronger parts of the field. Some examples of such kind of materials are aluminum, manganese, platinum, and oxygen. If a bar of paramagnetic material is suspended in between the pole pieces of an electromagnet, it sets itself parallel to the lines of force. When a bar of paramagnetic material is placed in a magnetic field the lines of force tend to accumulate in its Paramagnetic materials have a magnetization proportional to the field in which they are placed, following the same direction. With low ratio of the object magnetization to the field producing [62]. The magnetization of the paramagnetic material is showed in Figure 2-6

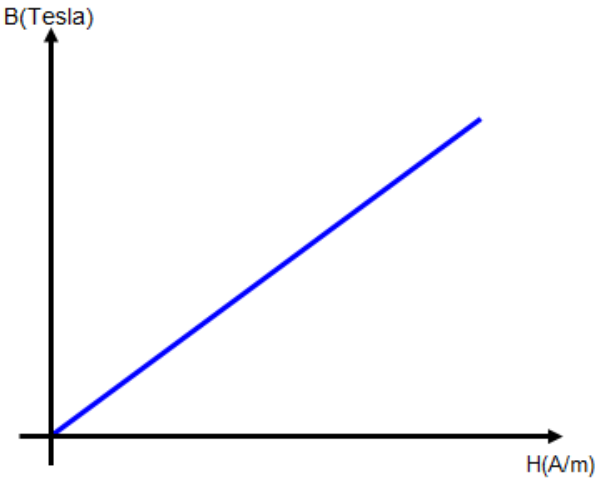


Figure 2-6: magnetization of a paramagnetic materiel.

**2.7.3 Ferromagnetic material**

Ferromagnetic substances are those which are attracted by the magnets and can also be magnetized. Iron, nickel, cobalt and their alloys are examples of these substances.

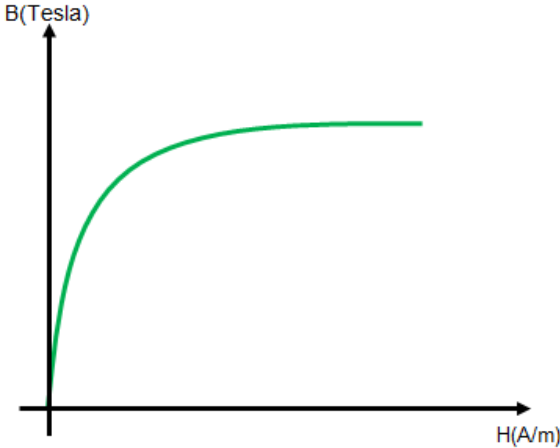


Figure 2-7: magntization of a ferromagnetic material.

Ferromagnetic substances show the properties of the paramagnetic substance to a much greater degree. The susceptibility has a positive value and the permeability is also very large. The intensity of magnetization  $I$  is proportional to the magnetizing field  $H$  for small value. Ferromagnetic materials are able to magnetize much more strongly. Their magnetizations follow the same direction as the induction field. It increases with the induction field until a certain limit value [62]. The magnetization of the ferromagnetic material is showed in Figure 2-5

**CHAPTER 3:  
MODLING OF MAGNETIC  
POLYMER COMPOSITE  
AND MICROPUMP  
MECHANISM**

### **3.1 Introduction**

Most physical phenomenon are expressed in the space-time dependent by the partial differential equations PDEs such as (magnetic, microfluidics ...etc.), and to resolve this equation numerically the finite element analysis FEA is used to give an approximation of the real solution of PEDs, which can be difficult to solve with analytic method.

In this chapter we will give a short definition of FEA, also introduce the basic tool of simulation who can solve the PEDs using a FEA, and finally define the steps of the simulation of a membrane magnetically actuated, and a mechanism of micropump using COMSOL Multiphysics.

### **3.2 Finite element method**

The finite element method (FEM) is a numerical technique used to obtain approximate solutions of problems which are described by partial differential equations. The first step to make the (FEM) works is to divide a solution region into finite elements. Secondly, select interpolation functions to interpolate the field variables over the element. Then, Find the element properties. After that, Assemble the element equations. To find the global equation system for the whole solution, and solve it. Finally Compute additional results to calculate additional parameters [63].

### **3.3 COMSOL Multiphysics**

The COMSOL Group was founded by Mr. Svante Littmarck and Mr. Farhad in Sweden in 1986 [64]. It has now grown to United Kingdom, U.S.A, Finland and so on. Nowadays, The COMSOL Multiphysics software has been widespread used in various domains of science research and engineering calculation, for example, it was used in global numerical simulation [64,65].

COMSOL Multiphysics is a finite element analysis, solver and Simulation software package for solving various physics and engineering applications. The first version of COMSOL Multiphysics software was published in 1998 by COMSOL group and it was named as Toolbox. The COMSOL Multiphysics simulation environment facilitates all steps in the modeling process: defining your geometry, specifying your physics, meshing, solving and then post-processing your results [65].

### 3.3.1 Theory for the magnetic fields, no currents interface

In magnetostatic problems where no electric currents are present, it is possible to formulate and solve the problem using a scalar magnetic potential. In a current-free region you have  $\nabla \times \mathbf{H} = \mathbf{0}$ . This implies that the magnetic scalar potential  $V_m$  can be defined from the relation  $\mathbf{H} = -\nabla V_m$ , which is analogous to the definition of the electric potential for static electric fields.

Using the constitutive relation  $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$ , the equation  $\nabla \cdot \mathbf{B} = 0$  becomes

$$-\nabla \cdot (\mu_0 \nabla V_m - \mu_0 \mathbf{M}) = 0 \quad (3.1)$$

The Magnetic Fields, No Currents Interface uses this equation for modeling of magnetostatics in the absence of electric currents [66].

### 3.3.2 Calculating electromagnetic forces and torques

Two methods are available to calculate electromagnetic forces and torques :

- The most general method is to use the Maxwell stress tensor.
- Another method that works for the special case of computation of magnetic forces on nonmagnetic, current-carrying domains uses a predefined physics interface variable for the Lorentz force distribution in a magnetic flux density  $\mathbf{B}$ .

#### ▪ Maxwell stress tensor

Force and torque calculations using Maxwell's stress tensor are available in the electrostatics, electric currents, magnetic fields, and magnetic and electric fields interfaces. In electrostatics and electric currents, the force is calculated by integrating (3-1) on the surface of the object that the force acts on.

$$\mathbf{n}_1 T_2 = -\frac{1}{2} \mathbf{n}_1 (\mathbf{E} \cdot \mathbf{D}) + (\mathbf{n}_1 \cdot \mathbf{E}) \mathbf{D}^T \quad (3.2)$$

In the Magnetic Fields interface, the expression

$$\mathbf{n}_1 T_2 = -\frac{1}{2} \mathbf{n}_1 (\mathbf{H} \cdot \mathbf{B}) + (\mathbf{n}_1 \cdot \mathbf{H}) \mathbf{B}^T \quad (3.3)$$

is integrated on the surface to obtain the force. In the Magnetic and Electric Fields interface, both expressions are included.  $\mathbf{E}$  is the electric field,  $\mathbf{D}$  the electric displacement,  $\mathbf{H}$  the magnetic field,  $\mathbf{B}$  the magnetic flux density, and  $\mathbf{n}_1$  the outward normal from the object [66].

- **Lorentz force**

The Lorentz force is defined as  $\mathbf{F} = \mathbf{J} \times \mathbf{B}$ . The Lorentz force is very accurate for electromagnetic force calculations in electrically conducting domains. The Lorentz force variables are available both in domains and on boundaries (in the case of surface currents) [66].

### 3.4 Simulation of membrane magnetically actuated

Polymeric membrane actuators have been extensively employed as components in diverse technological systems, especially in the microfluidics one's due to their biocompatibility and low cost. By adding a dispersed magnetic particle in the polymeric matrix, this one acquires a magnetic property and this polymer-nanoparticles composite will have a motion due to an external magnetic field, in this section we will simulate a cylindric membrane, and its behavior in a constant magnetic flux.

The membrane made of dispersed superparamagnetic nanoparticles in PDMS matrix [49].

#### 3.4.1 Geometry discription

For the simulation of a cylindric membrane (with radius =5mm and thickness =300 $\mu$ m), we use a 3D geometry (see Figure 3-1), and add the Magnetic Fields No current and Solid mechanics interfaces as well as the Stationary study type.

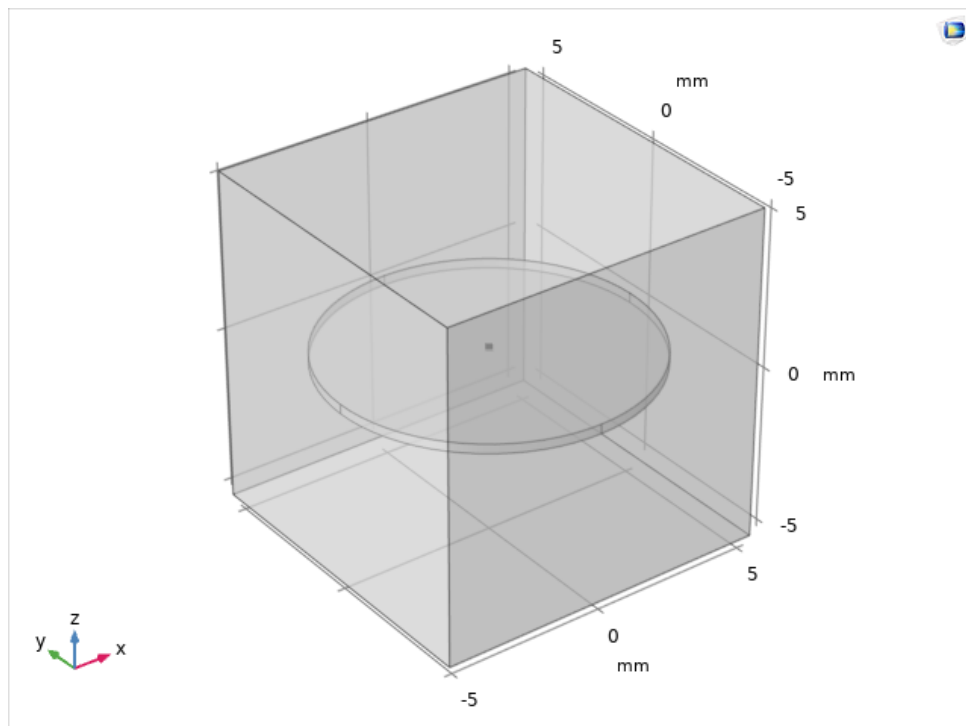


Figure 3-1: Model geometry in COMSOL Multiphysics.



### 3.4.2 Model parameters

For the simulation under COMSOL we have chosen Parameters in the Figure 3-2 :

Parameters			
Name	Expression	Value	Description
BB0	0[mT]	0 T	applied magnetic flux in the z direction
memD	5[mm]	0.005 m	membrane Radius
memH	0.3[mm]	3E-4 m	membrane thickness

Figure 3-2: Model Parameters.

### 3.4.3 Generating a constant magnetic field

To apply a constant magnetic flux normal to the surface of the membrane, we use the Magnetic flux density node. Figure 3-3 shows how we apply the magnetic field in COMSOL Multiphysics.

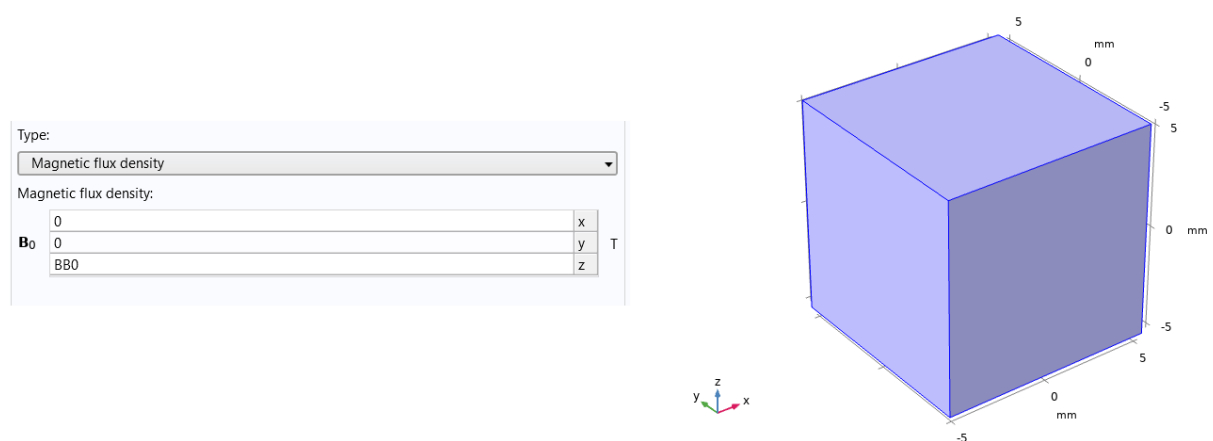


Figure 3-3: Application of the constant magnetic field in COMSOL Multiphysics.

### 3.4.4 Compute the electromagnetic force

The force calculation node in the MFNC interface help us to compute the electromagnetic force applied on the membrane, we can then add it manually on the Body Load in the solid mechanics interface which apply a mechanical force on the membrane (Figure 3-4).

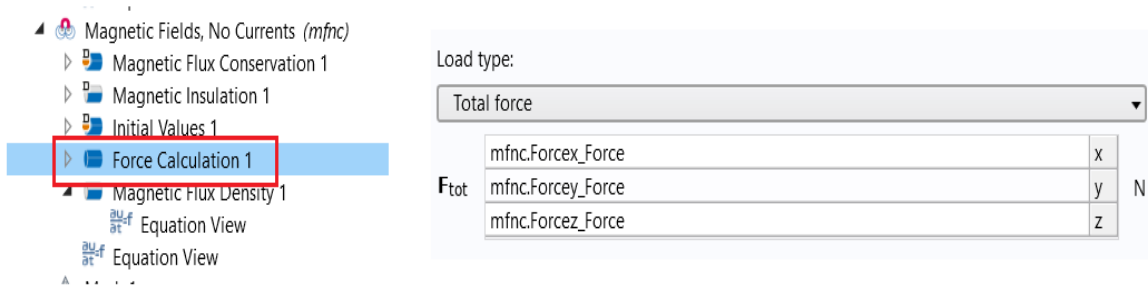


Figure 3-4: Computing the electromagnetic force in COMSOL Multiphysics.

### 3.4.5 Fixed boundaries

We fix boundaries of the membrane shown in Figure 3-5.

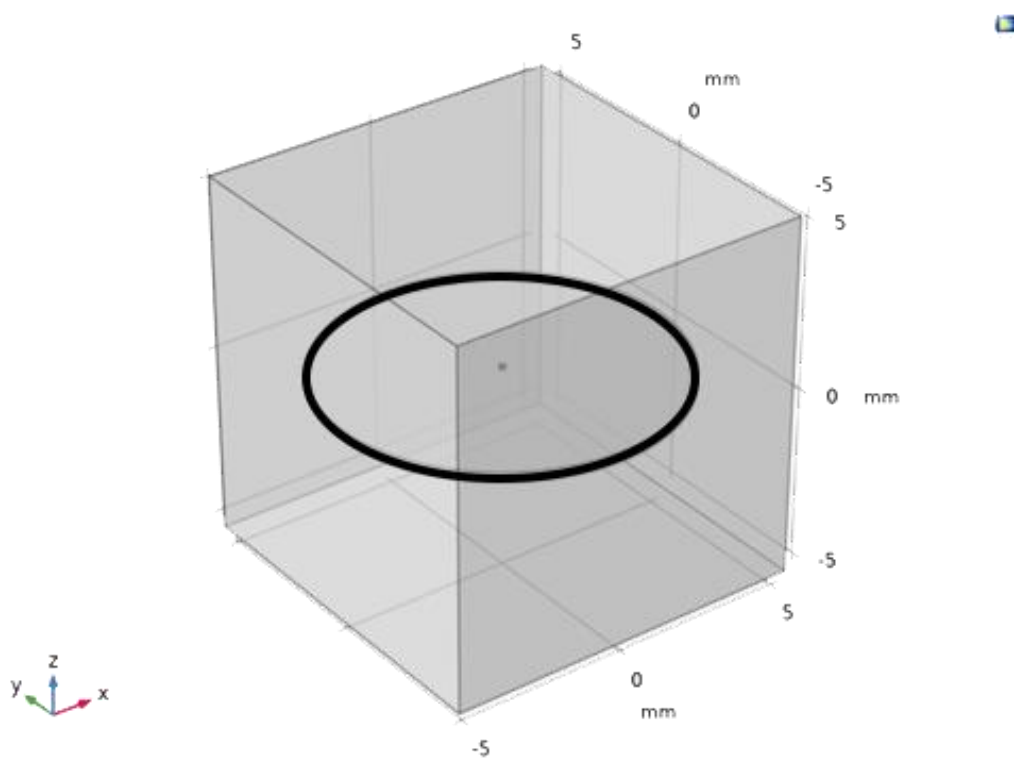


Figure 3-5: fixed boundaries

### 3.4.6 Material proprieties

Adding a dispersed magnetic nanoparticle in the polymer membrane, influence some material proprieties like Young's module, also it will add a new magnetic propriety change according to MNP's type and concentration, in this section we will define our material proprieties for different concentration of MNP's.

### 3.4.6.1 Young's module

Due to their low Young's module, Fahrani et al choses the Sylgard PDMS as a polymeric matrix with a dispersed iron oxide nanoparticles (superparamagnetic), and measured experimentally the change of the elastic module E in function of the change of the concentration of the magnetic materiel (Figure 3-6) [49].

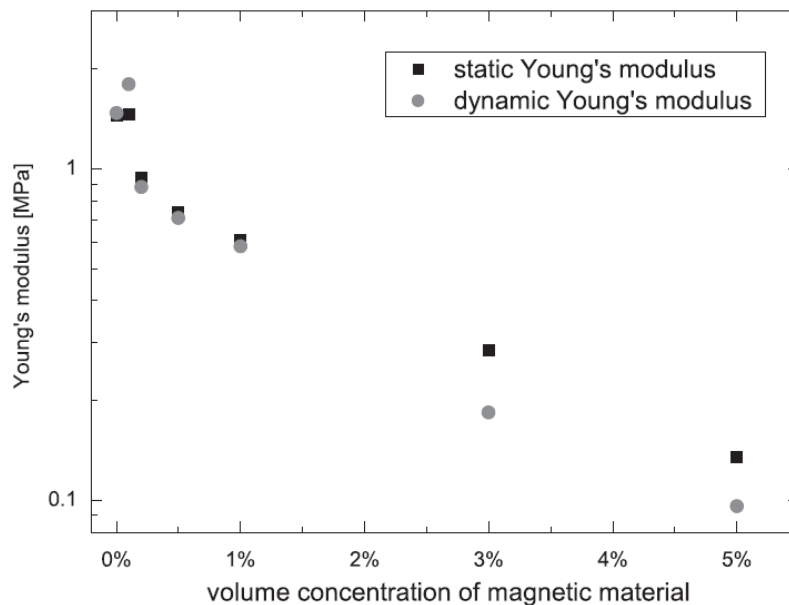


Figure 3-6: Elastic modulus measured for PDMS as function of the volume concentration of dispersed superparamagnetic nanoparticles [49].

### 3.4.6.2 Magnetic proprieties

Magnetic properties of polymer magnetic composite materials depend on the form, type of filler and on chosen manufacturing technology [39].

- **Magnetic properties at high frequencies**

The magnetic permeability has been considered the most important property in particular polymer composites. The magnetic permeability at high frequencies of Fe-polymer, Ni-polymer, Co-polymer and Fe-Co-Ni polymer composites are studied in the following discussion. Figure 3-7 shows the magnetic permeability values of Fe-, Ni-, Co-, and Fe-Ni-Co polymer matrix composite. From the curve it is clear that Fe polymer composite reveals the highest magnetic permeability compared to other composites for frequencies lower than  $1.5 \times 10^6$  Hz. When the frequencies continue to rise, its magnetic permeability drops, and this decline was observed to be higher in case of Fe-polymer composite compared to others. At a frequency starting at  $1.2 \times 10^7$  Hz, the magnetic permeability of Fe-polymer, Co-polymer and Ni-polymer composite (26, 28.5,

45.5 respectively) were lower than that of the Fe-Ni-Co polymer Composite ( $\mu=54$ ). It is concluded from this results that the magnetic permeability of the powder-polymer composite is governed by the metallic powder volume fraction Since Ni and Co occupy 60vol% while the volume occupied by the Fe is 27% and the rest was attributed to the resin and residual porosity [67].

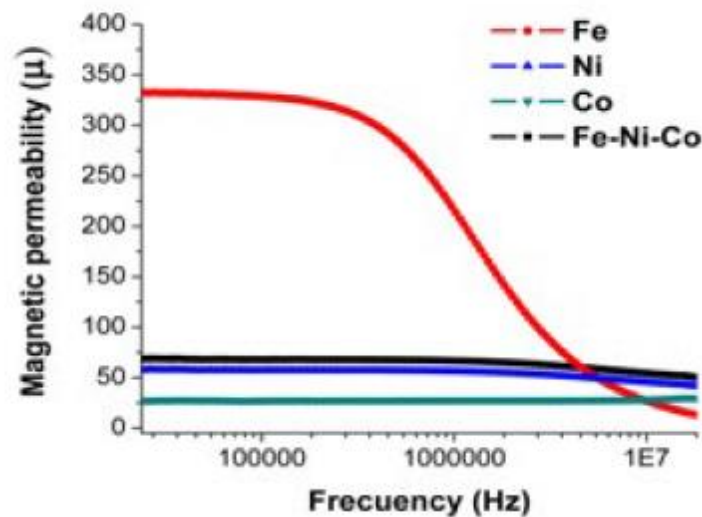


Figure 3-7: Magnetic permeability evolution as a function of the AC frequency of the magnetic field [67].

- **Physical condition effect on composite magnetic parameters**

The line graph in Figure 3-8 a illustrates the effective permeability  $\mu_{\text{eff}}$  versus statistical mean value of grain size  $\langle D \rangle$  behavior for specific mass concentration of ferrite filler added in PVA polymer. It shows that the specimen with 90 wt% concentration of the filler possesses the highest value of the effective magnetic permeability  $\mu_{\text{eff}} = 21$  corresponding to the highest value of the grain size dimension  $\langle D \rangle$  compared to other specimens. On the other side, where the DC magnetic field is applied (Figure 3-8 b), the directions of the toroidal plane is perpendicular to the DC magnetic field. From these results, the orientation impact is noted of the applied field on the ferrite particles. During the preparation of the specimens a critical growth of the effective magnetic permeability is observed for the 85wt% specimen compared to 93wt% specimen. It can be deduced that there is more likely reinforced interaction between the ferrite particles and the thin diamagnetic polymer layer on the interface ferrite particles-polymer matrix. This effect consists in a direct super exchange interaction between unpaired electron spins through - OH...O- hydrogen bond [68].

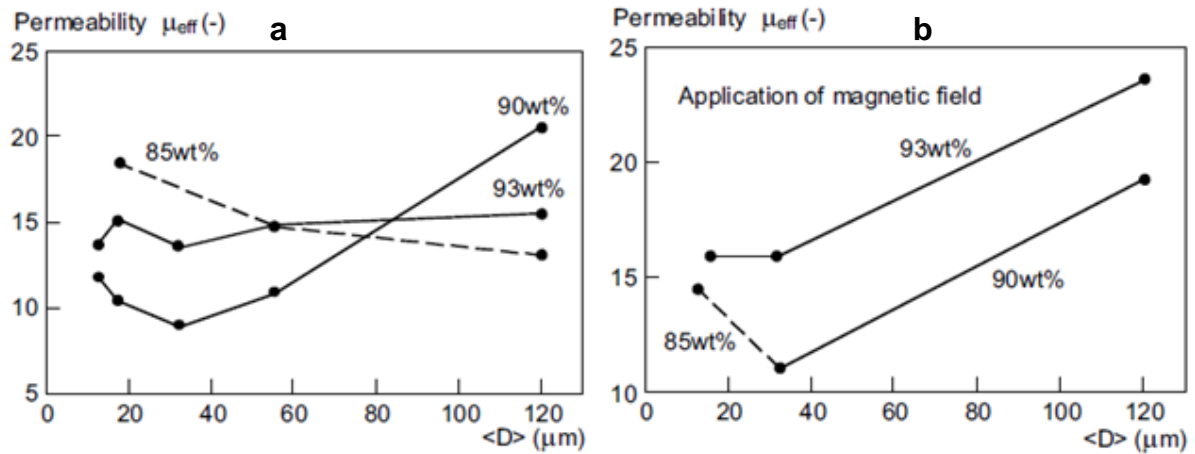


Figure 3-8: The dependence of effective permeability  $\mu_{eff}$  on the statistical mean value of grain size  $\langle D \rangle$  (a) without application of DC magnetic field (b) with application of a DC magnetic field [68].

In case of changing the polymer type to PVC polymer as diamagnetic matrix, analogous analysis was achieved, and the temperature dependence of the magnetic flux  $\Phi$  measured on the two samples with different concentrations of the ferrite filler (while the particle size maintained) is shown in Figure 3-9. It can be observed for the two polymer composites, the magnetic flux  $\Phi$  is inversely proportional to the temperature [68].

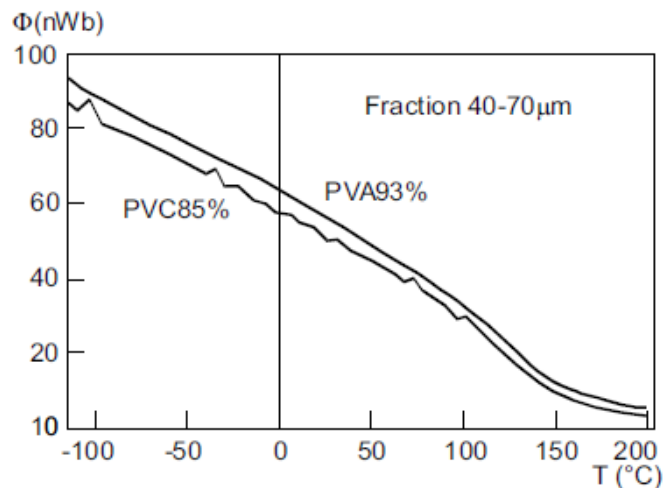


Figure 3-9: Temperature dependence of the magnetic flux for ferrite- polymer composites [68].

- **Magnetic susceptibility**

In the presence of a magnetic field, the magnetization per particle  $M_{part}$  can be described by a balance between the magnetic energy and the thermal relaxation of the particles, with the help of the Langevin equation:

$$M_{part} = \sum r_i M_{sat} \left[ \coth \left( \frac{\mu_0 M_{sat} V_i H}{k_B T} \right) - \frac{k_B T}{\mu_0 M_{sat} V_i H} \right] \quad (3.4)$$

with  $r_i$  being the volume concentration of particles with volume  $V_i$ ,  $M_{sat}$  the saturation magnetisation of bulk magnetite,  $\mu_0$  the permeability of vacuum,  $H$  the applied magnetic field,  $k_B$  the Boltzmann constant and  $T$  the temperature [49].

For low magnetic fields, the Langevin equation has a linear asymptote:

$$M_{part} = \sum r_i \frac{\mu_0 M_{sat}^2 V_i}{3 k_B T} H = \chi_L H \quad (3.5)$$

$\chi_L$  being called the initial magnetic susceptibility.

Huke and Lücke [69,70] introduced a correction factor  $I_1$  on the quadratic term of this expansion to account for particle aggregation and the initial susceptibility is thus expressed as:

$$\chi_{ini} = \frac{1}{C_v} \left[ C_v \chi_L + I_1 \left( \frac{\chi_L}{8} \right) \cdot \frac{(C_v \chi_L)^2}{3} + \frac{(C_v \chi_L)^3}{144} \right] \quad (3.6)$$

with Huke's factor defined as  $I_1$ ,  $C_v$  the magnetic volume concentration in the ferrofluid, and  $\chi_L$  the initial magnetic susceptibility [49].

According to equation (3.4), farhani et al calculate the initial susceptibility of particles in ferrofluid with and without Huke's factor, which is very close to the experimental values (Figure 3-10).

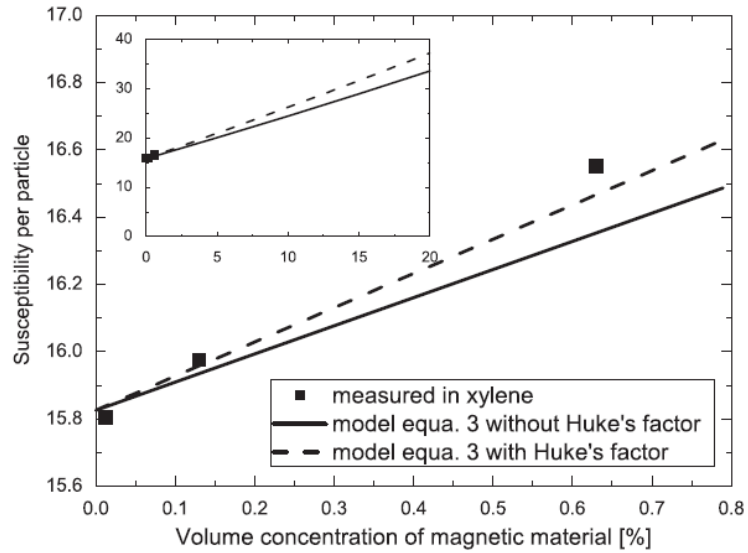


Figure 3-10: Initial magnetic susceptibility per particle for several concentrations [49].

Iron oxide (with size around 10nm) and the Sylgard PDMS have been mixed to create a magnetic PDMS simple with different particle concentration.

The magnetic PDMS has a lower susceptibility ( $\chi=10.0$ ) than a ferrofluid ( $\chi=15.8$ ) with the same particle concentration. And The most likely reason for a lower magnetization in PDMS is that aggregation of particles experience local demagnetization [49]. Figure 3-11 shows an illustration of nanoparticles cluster in PDMS.

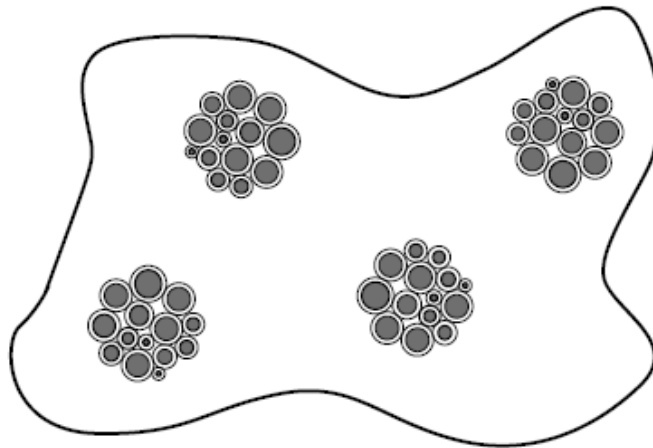


Figure 3-11: Illustration of clusters of superparamagnetic nanoparticles in a polymer [49].

### 3.4.6.3 Material definition

We consider that the magnetic particles have been dispersed uniformly in the magnetic PDMS membrane without cluster, and we extract the theoretical result of the initial magnetic susceptibility for different volume concentration of MNP in the composite from Figure 3-10.

Table 3-1: Magnetic and mechanical properties for different particle concentration.

Material name	Concentration of MNP in PDMS	Young's Module (MPa)	Initial Susceptibility	Relative Permeability
Mat1	1%	0.60954	16.576	17.576
Mat2	2%	0.43	17.647	18.647
Mat3	3%	0.28462	18.827	19.827
Mat4	4%	0.20357	19.898	20.898
Mat5	5%	0.13423	20.921	21.921

when we consider that there is no cluster in the PDMS composite, the initial magnetic susceptibility  $\chi=15.8$ , but when the clusters have 11% of the magnetic material the initial magnetic susceptibility decrease to 10.0.[49] in Table 3-2 we resume the magnetic and the mechanical properties for the magnetic PDMS composite without cluster (MatNC), and with cluster (MatWC) for 3% volume concentration of magnetic material in the composite.

Table 3-2: Magnetic and mechanical properties for polymer composite with and without clusters.

Material name	Concentration of MNP in PDMS	Young's Module (MPa)	Initial Susceptibility	Relative permeability
MatNC	3%	0.28462	18.827	19.827
MatWC	3%	0.28462	13.22344	14.22344



### 3.4.7 The meshing

To get an accurate force computation, we need a particularly extremely fine mesh on the membrane (Figure 3-12).

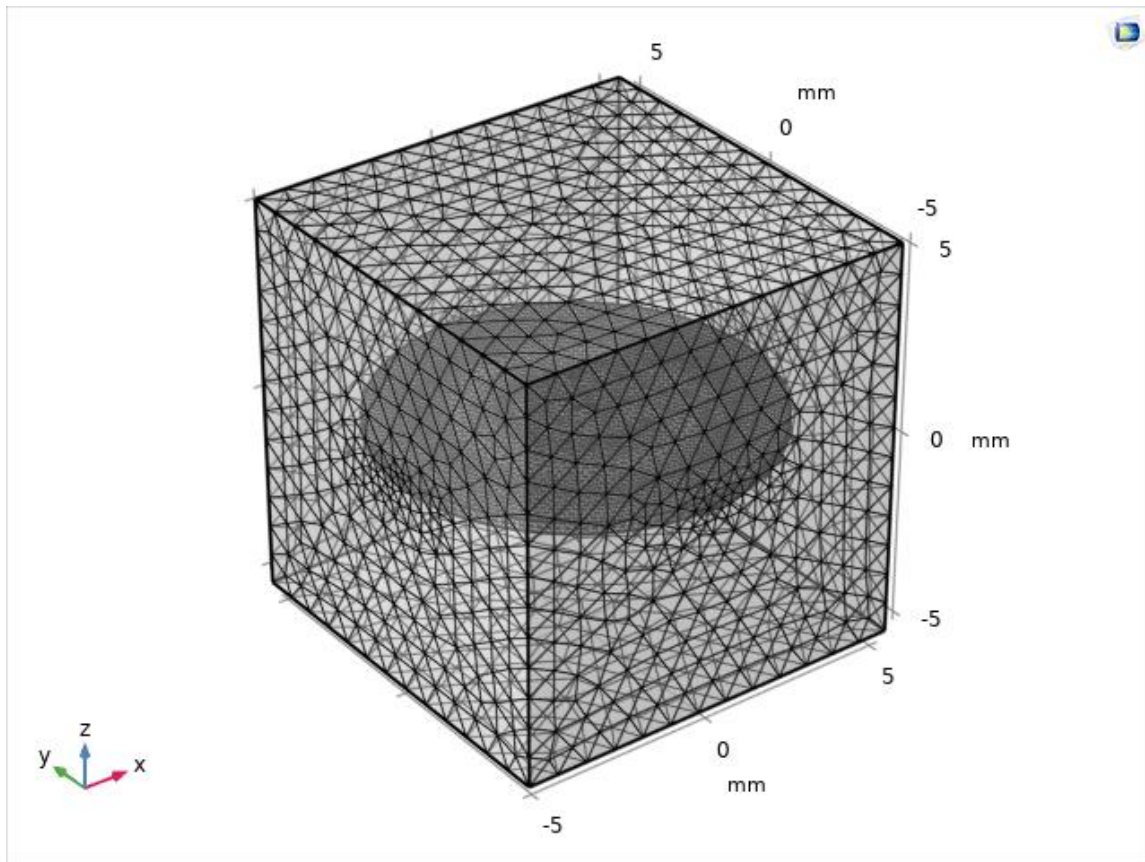


Figure 3-12: Meshing of the model in COMSOL Multiphysics.

## 3.5 Simulation of micropump mechanism

### 3.5.1 Introduction

Many valves pump designs are unsuitable for viscous fluids and applications with low flow rates. Due to the difficulty for achieving sustained flow in a given direction without valves [71]. To overcome this limitation, a mechanism simulated in this model to convert oscillatory fluid into a net flow in one direction. In a microfluidic system, it is simple to create an oscillatory pumping mechanism. e.g. a membrane can be vibrated by a magnetic actuator to periodically vary the volume of a microchamber. We have started this model from a basic model in COMSOL library entitled "micropump mechanism".

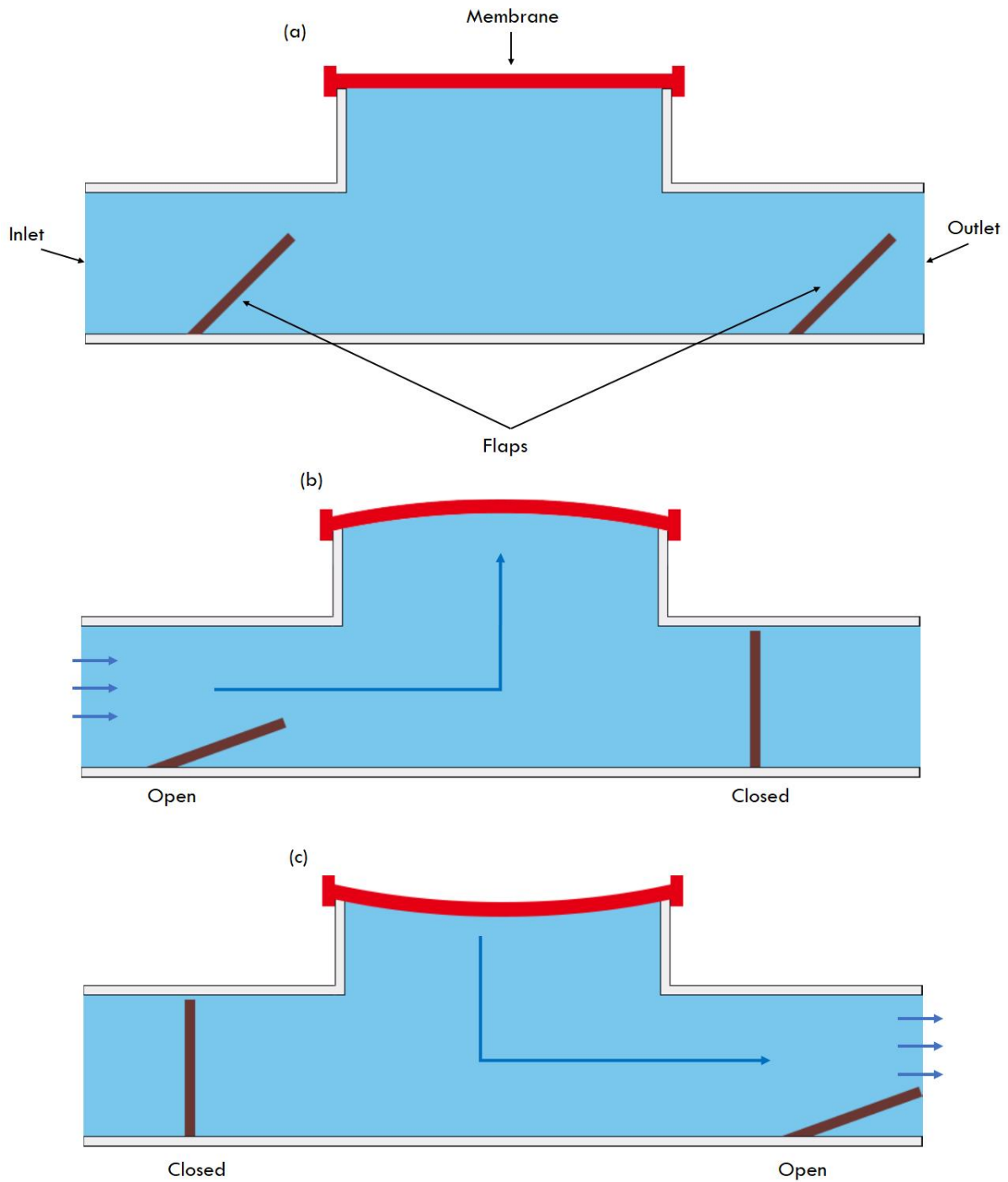


Figure 3-13: Illustration of micropump mechanism

In this model, an oscillatory flow is fed into a channel including bendable micro flaps. By virtue of their deformation, the flow changes into a net flow rate in a one direction. The simulated micropump composed of horizontal microchannel connected to a vertical chamber, at the top of this chamber there is an actuated membrane, two flaps are attached to the bottom of the microchannel, one at the inlet and the other at the outlet (see Figure 3-13 a). When the membrane move up the inlet flap is open and the

outlet flap is closed due to the pumped fluid into the vertical chamber (Figure 3-13 b), when the membrane move down the fluid is pumped out (the outlet flap is open and the inlet flap is closed) see Figure 3-13 c. The Fluid-Structure Interaction Multiphysics interface is used to define the input oscillatory flow, and the flaps mechanical properties. The flaps deformation, and the fluid flow, is calculated as a function of time. Allowing the physical mechanism to be visualized using an animation. integration coupling components, the Global ODEs and DAEs interface are used to calculate the net volume pumped from left-to-right as a function of time. This is an example of how the functionality of one COMSOL interface can be improved by using a custom equation specified in a mathematics interface [71].

### 3.5.2 Model parameter

Table 3-3: Micropump mechanism model paramater.

Re [1]	16	Reynolds number
Coeff [1]	$4/\sqrt{\text{Re}}$	Coefficient to change Reynolds number
Dens [kg/m <sup>3</sup> ]	1000	Fluid density
Visc [Pa*s]	$0.001*\text{coeff}$	Fluid dynamic viscosity
U [cm/s]	$16/\text{coeff}$	Average inlet flow speed
H [μm]	100	Channel height
W [μm]	10	Domain width
rp [μm]	2	Pillar radius
hp [μm]	70	Pillar height
L [μm]	600	Length of channel
beta [deg]	45	Flap tilt angle
x0 [μm]	150	Flap center location
Re_check [1]	$\text{dens}*U*H/(\text{visc})$	Reynolds number

### 3.5.3 Model definition

The Figure 3-14 shows a 2D model geometry containing a horizontal channel that is 600 μm in length and 100 μm high. A vertical chamber connects to the channel midpoint. Two tilted flaps are attached to the channel bottom. They are both angled at 45 degrees to the horizontal channel edge and spaced to be centered on the channel length [71].

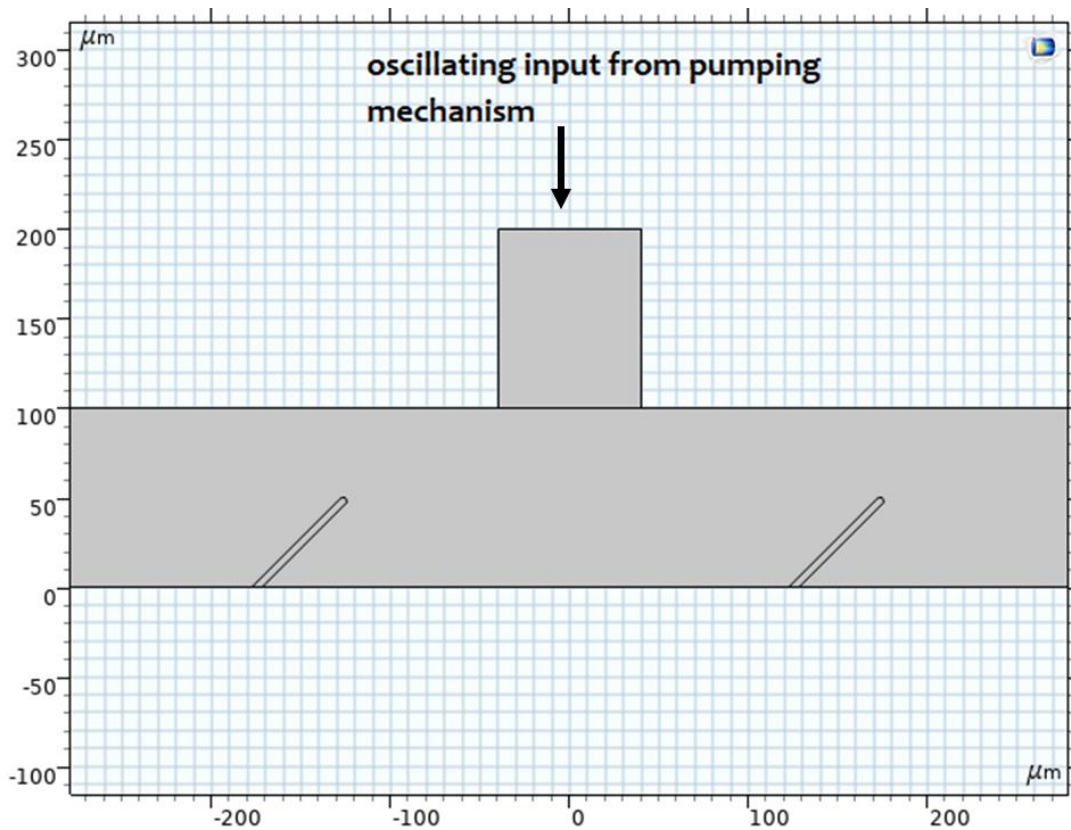


Figure 3-14: Model geometry

In this physics, an Inlet boundary is applied to the chamber top. This indicates the inflow velocity, via a user input expression, to vary sinusoidally in time with a period of 1 s. An Outlet boundary is applied to the left and right boundaries of the channel. To compute the flow rate out of each outlet, two integration coupling components for the left and right are applied to these boundaries. This is calculated by integrating  $u_{\text{fluid}}$ , the horizontal component of the fluid velocity, and multiplied by the out-of-plane length scale. Therefore, the net flow rate out of the channel  $U_{\text{outNet}}$ , is calculated from the difference between the flow from the left and right outlets [71].

To compute the integrated net flow, a Global ODEs and DAEs interface is added. This is achieved using a Global Equation which integrates  $U_{\text{outNet}}$  (it gives the instantaneous net flow rate as a function of time) with respect to time to obtain  $V_{\text{pump}}$ . The mesh is formed to be tightest around the tilted flaps, for resolving the stress within the bending flaps. The mesh is shown in Figure 3-15 [71].

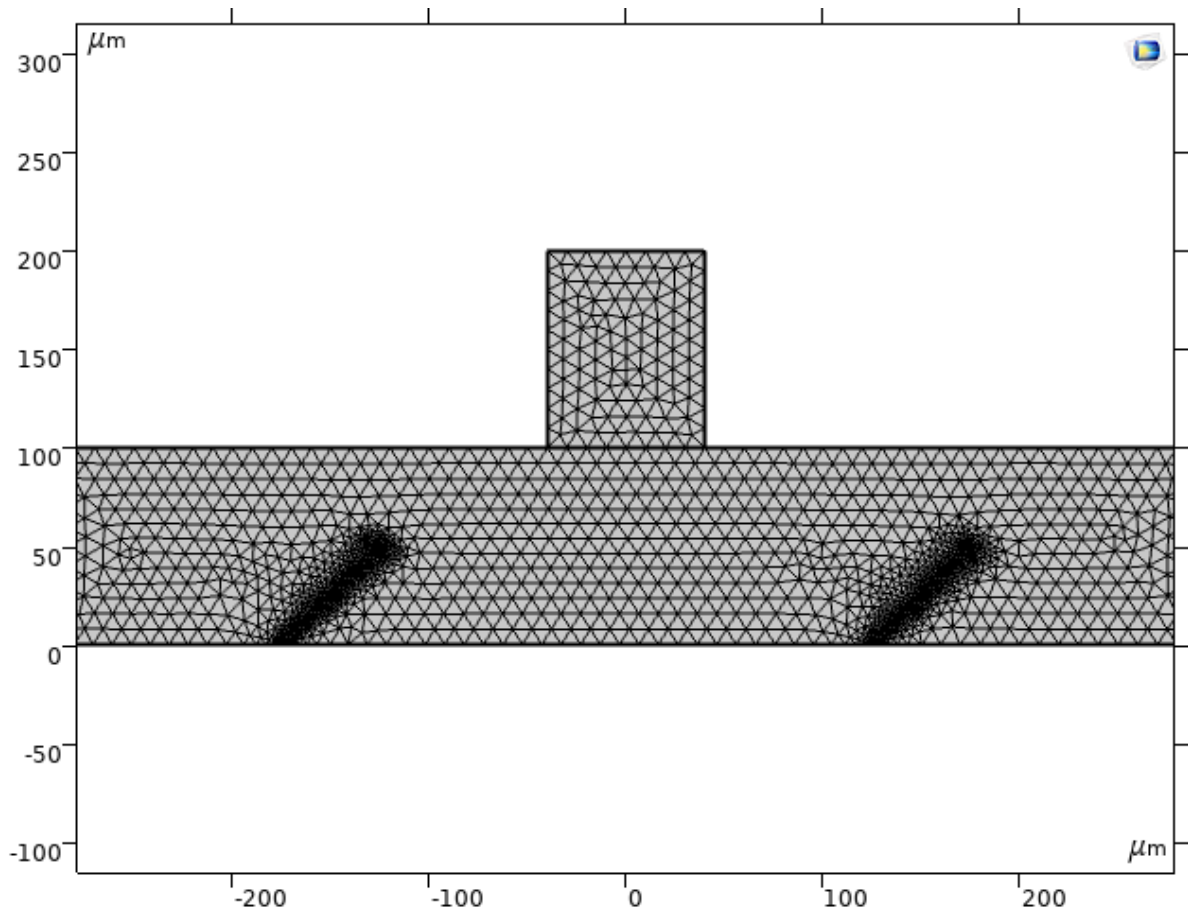


Figure 3-15: Model Meshing

A single time dependent study is performed in 2 seconds, corresponding to two oscillations of the inlet velocity. The Time Stepping sets the maximum to 0.01 s. this is required due to the potential for sudden changes to the fluid flow in fluid-structure interaction models. Allowing the solver to vary the time step it takes so that larger steps can be taken during times when the solution is not rapidly altering [71].

Note that the geometry is parameterized such as channel dimensions, flap angle, the average flow rate at the inlet and the fluid properties by amending the relevant entry in the Global Parameters table. The effective Reynolds number can be also changed as the viscosity and average inlet velocity are scaled by a shared coefficient that is computed from the target Reynolds number [71].

# **CHAPTER 4:**

# **RESULTS & DISCUSSION**

### 4.1 Magnetization and Magnetic Field

Figure 4-1 shows the applied magnetic flux density in the membrane of a 5mm diameter and 300µm in thickness, the applied magnetic field equal to 200mT in the center of the membrane. Figure 4-2 shows the magnetization of the membrane for 200mT applied magnetic field, the value of the magnetization in the center of the membrane is constant and equal to  $1.5 \times 10^5 \text{A/m}$  respecting the law of the magnetization  $M = \chi H$ , in the edge of the membrane the value of the magnetization vary from  $2 \times 10^5 \text{A/m}$  to  $5 \times 10^5 \text{A/m}$ , and the value of the applied magnetic field change from 200mT to 400mT, because this edges are close to the boundaries of air domain which is applied the magnetic flux density.

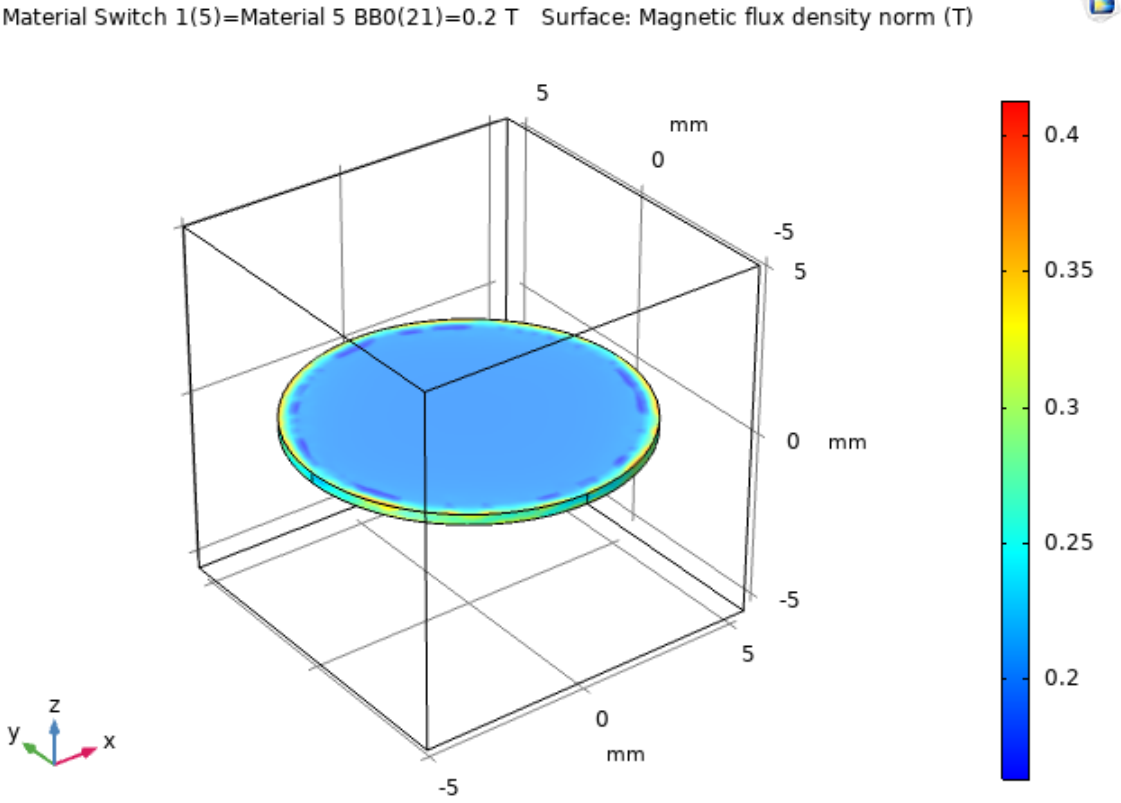


Figure 4-1: Magnetic flux density.

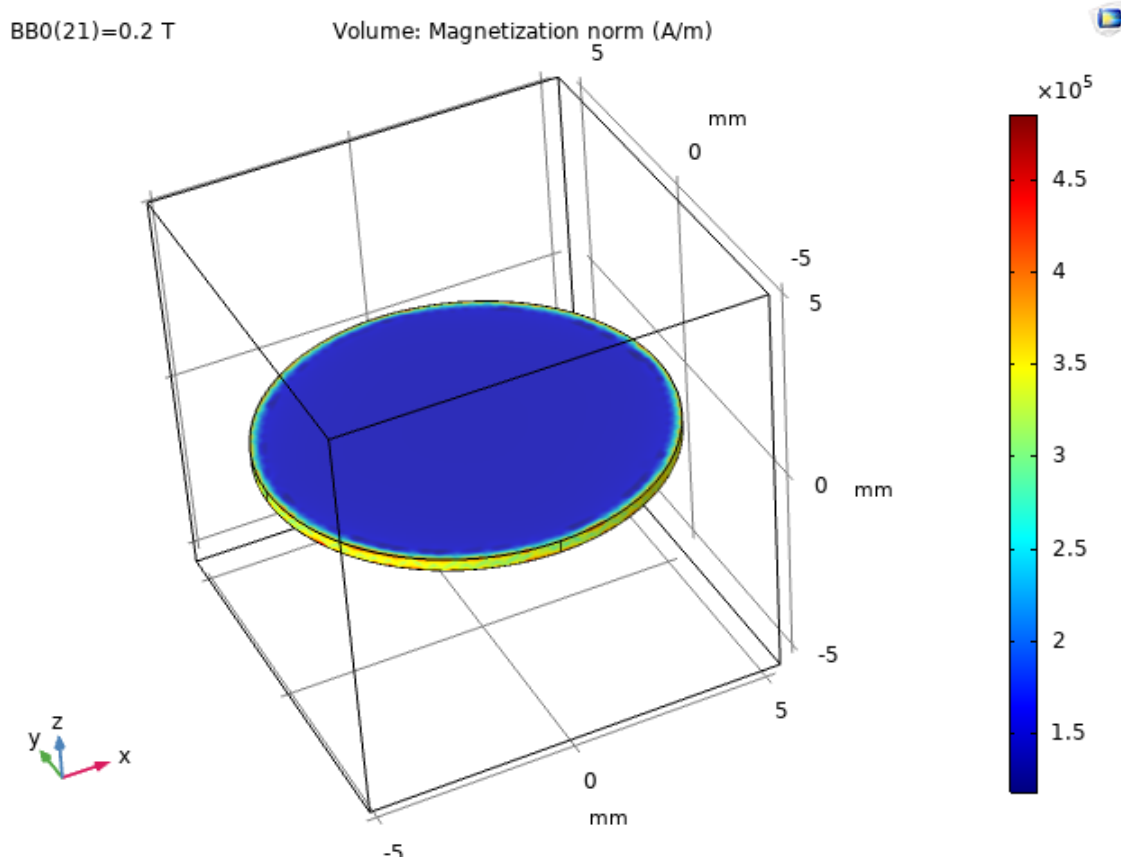


Figure 4-2: Magnetization of the membrane.

## 4.2 The electromagnetic force and the deflection of the membrane

The force on the membrane is calculated internally as an integral of the surface stress tensor over all boundaries of the rod. The expression for the stress tensor reads

$$\mathbf{n}_1 T_2 = -\frac{1}{2}(\mathbf{H} \cdot \mathbf{B})\mathbf{n}_1 + (\mathbf{n}_1 \cdot \mathbf{H})\mathbf{B}^T \quad (4.1)$$

where  $\mathbf{n}_1$  is the boundary normal pointing out from the membrane and  $T_2$  the stress tensor of air.

The calculated force was applied on Body Load node in structural mechanics physic to combine this tow physics (Magnetic Field No Current and Structural Mechanics), Figure 4-3 shows the deflection of the membrane under the electromagnetic force calculated. The displacement of the center of the membrane is 258  $\mu\text{m}$  under 200mT for a membrane with 300 $\mu\text{m}$  in thickness and 5mm in diameter.



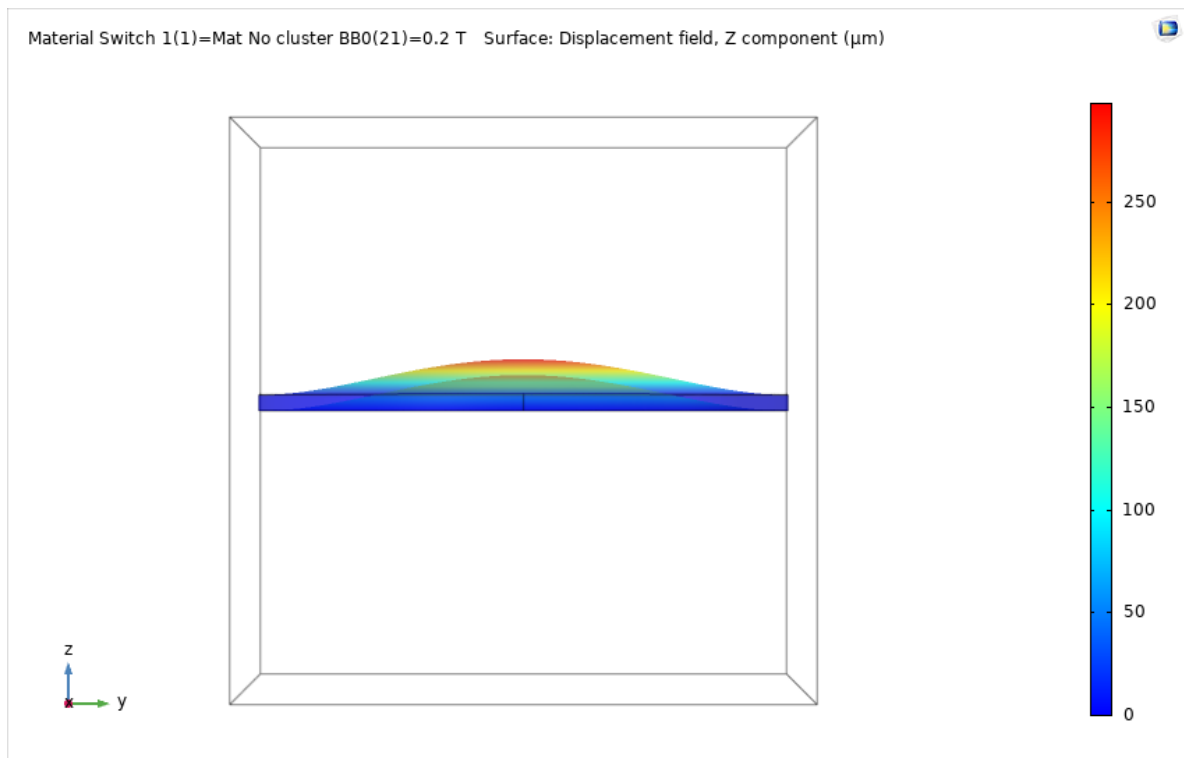


Figure 4-3: Deflection of the membrane under the magnetic field.

#### 4.3 Deflection of the membrane for different MNP's concentration

To evaluate the appropriate magnetic content of the composite films that leads to the highest magneto-responsivity, we simulated the deflection of the composites loaded with up to 5 % volume concentration of MNPs. Figure 4-4 shows the displacement of the center of the membrane which increase with the increase of the concentration of the MNPs in the composite, the maximal displacement achieved under an external magnetic field of 200 mT is 258 µm for the 5 % vol concentration.

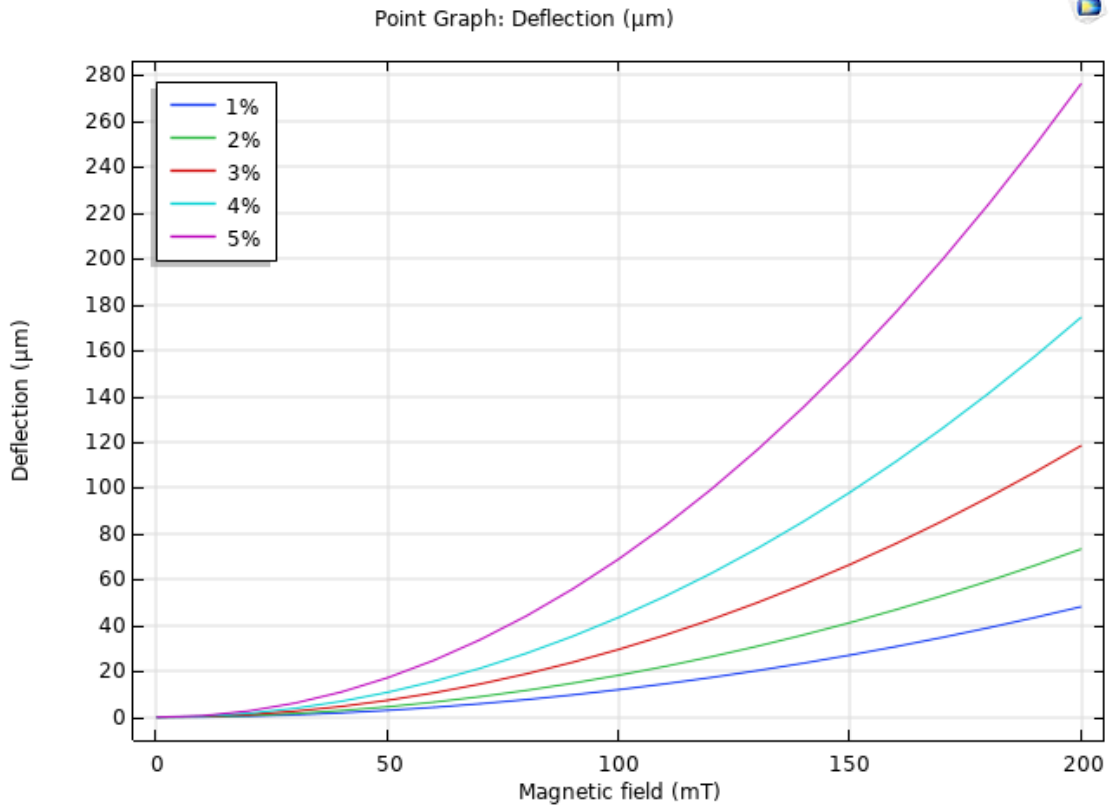


Figure 4-4: Deflection of the membrane for different MNP's concentration.

#### 4.4 Optimization of the material properties

A further increase in Magnetic content induce an increase in the relative permeability which improve the deflection of the membrane, in the other hand the progressive addition of rigid particles within a soft polymeric matrix leads to an increase in the film's stiffness that hinders its deformation upon the effect of the external field even if the magnetic content is increased. Figure 4-5 show both magnetic and mechanical proprieties. Consequently, the right compromise between elastic properties and the amount of particles should be identified for the optimal performance of the composite and in this case is revealed to be 3 %.

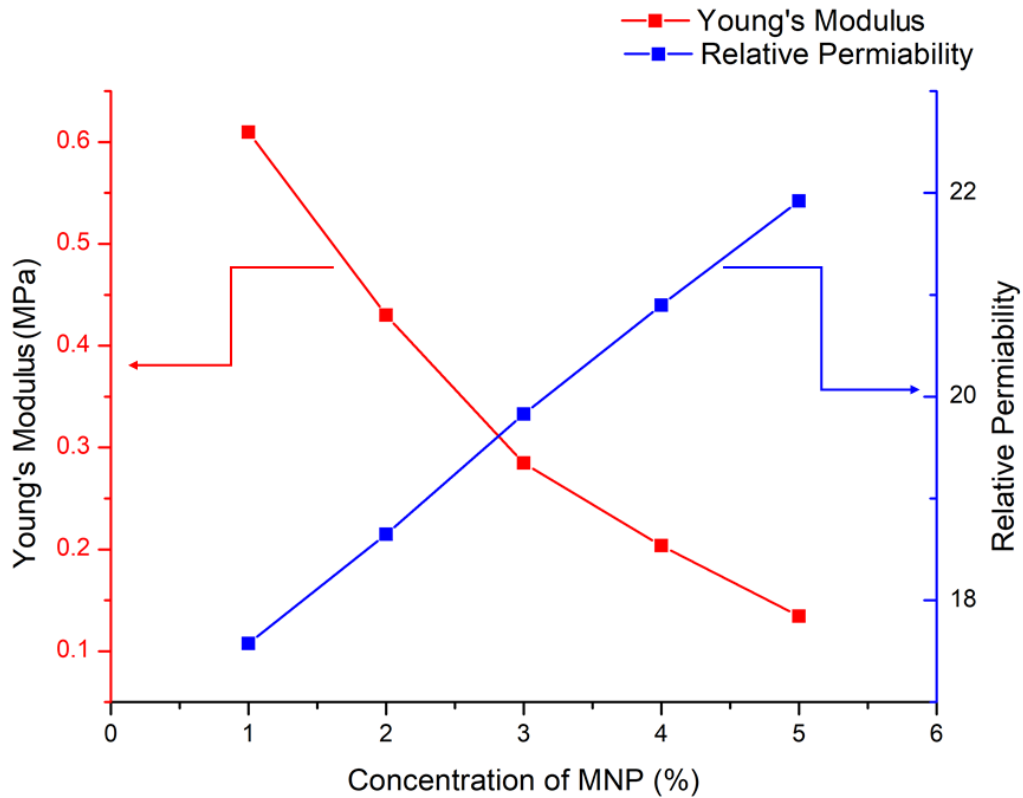


Figure 4-5: Magnetic and mechanical properties of composite.

#### 4.5 Cluster effect on the deflection of magnetic polymer membrane

Superparamagnetic particles dispersed in PDMS, with a maximum cluster size of 5  $\mu\text{m}$ . Fahrni et al hypothesize that the superparamagnetic particle clusters are not interconnected and that the mechanical properties of the composite are therefore determined mainly by the PDMS network, the magnetic PDMS has a lower susceptibility, the most likely reason is that clusters of particles experience local demagnetization. If the concentration of the magnetic material in the cluster is zero the magnetic susceptibility of the MNP equal to 15.8, with the increase of the concentration of the magnetic material in the cluster the magnetic susceptibility decrease, and reach 10.0 for 11% of concentration Figure 4-6 [49].

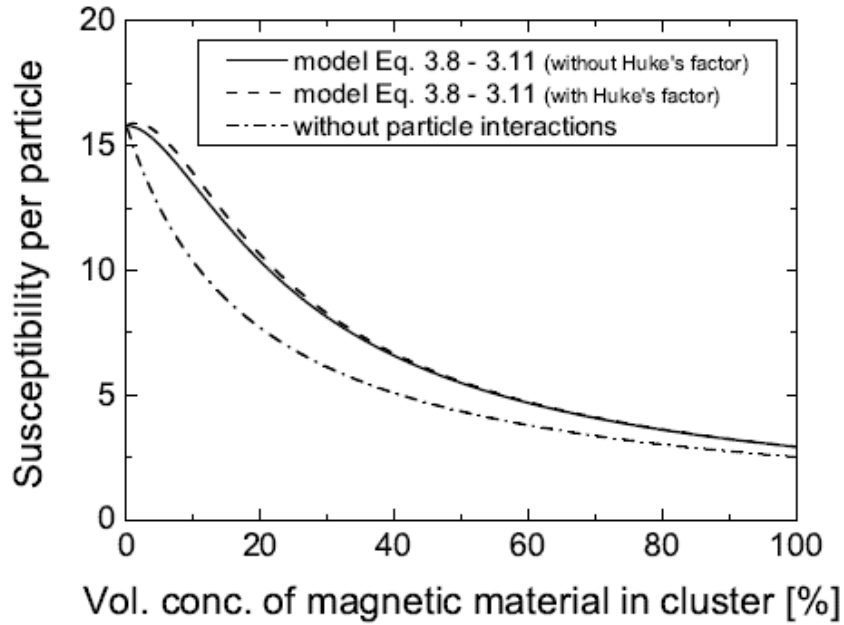


Figure 4-6: Magnetic susceptibility per particle for clustered particles dispersed in PDMS, as function of the magnetic volume concentration in the clusters [49].

We used the Langevin equation with Huk's factor to calculate the magnetic susceptibility for 3% volume concentration of MNP's in PDMS for tow type of materiel one when the magnetic susceptibility equal to 15.8 and the other when  $\chi = 10.0$ , for this concentration the Young's Modulus of the composite attain  $1.3 \times 10^5$  Pa. Figure 4-7 shows the deflection of the membrane for the tow material type (PDMS with MNP cluster and without cluster) under a low magnetic field. We remark that for the magnetic PDMS without cluster the deflection is higher than that of the magnetic PDMS with cluster.

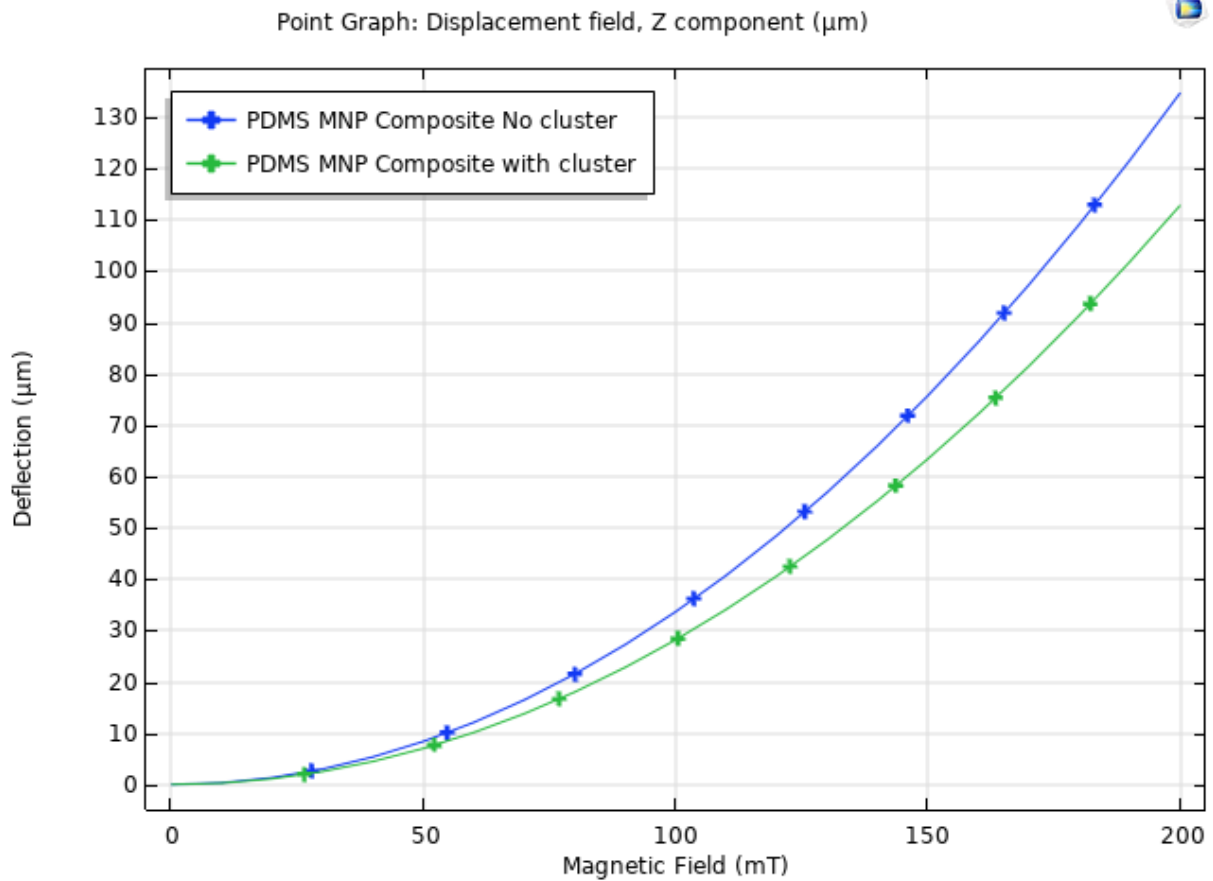


Figure 4-7: Deflection of the membrane for the tow type of material with and without cluster.

#### 4.6 Geometry effect on the deflection of magnetic polymer membrane

The dimension of the membrane played an important role on their deflection, as shown in Figures 4-8 and 4-9, the displacement of the center of the membrane increase with the decrease of the thickness, and the increase of the diameter of the membrane.

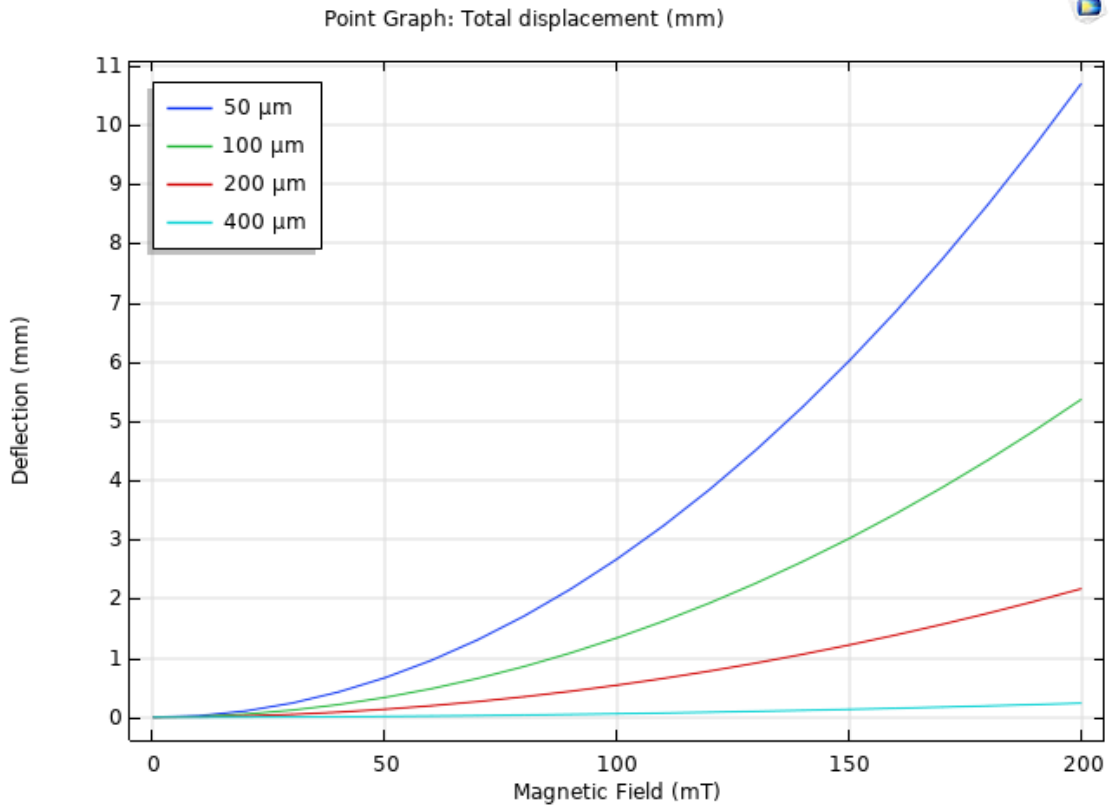


Figure 4-8: Deflection of the membrane for different thickness.

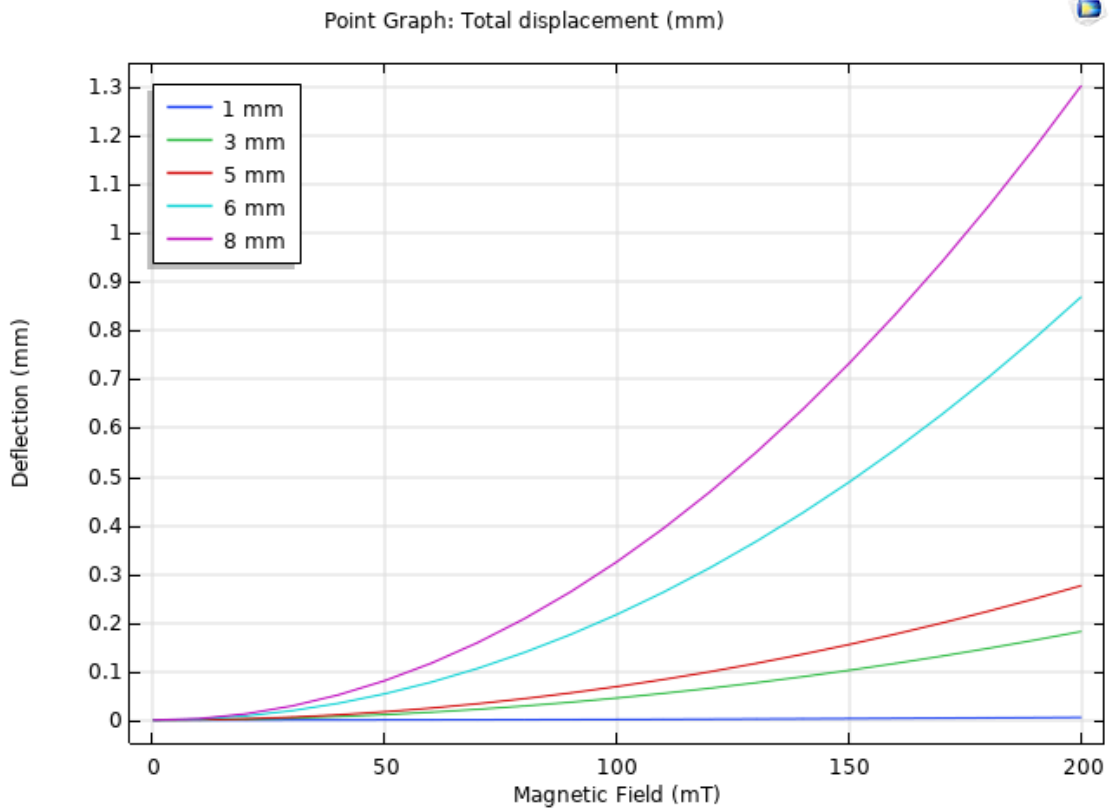


Figure 4-9: Deflection of the membrane for different diameter.

## 4.7 Micropump mechanism

Figure 3-13 exhibits the mechanism by which the flow direction is regulated can be observed in a combined Flow and Stress plot. The solution at 0.26 s, when fluid is pushed from the chamber, the right flap is bent down towards the bottom while the left flap is bent away from the channel bottom (see Figure 4-10). Corresponding to when the velocity flowing into the vertical chamber via the inlet is at its maximum. Because of the flaps asymmetric bending, fluid can easily flow out of the right outlet.

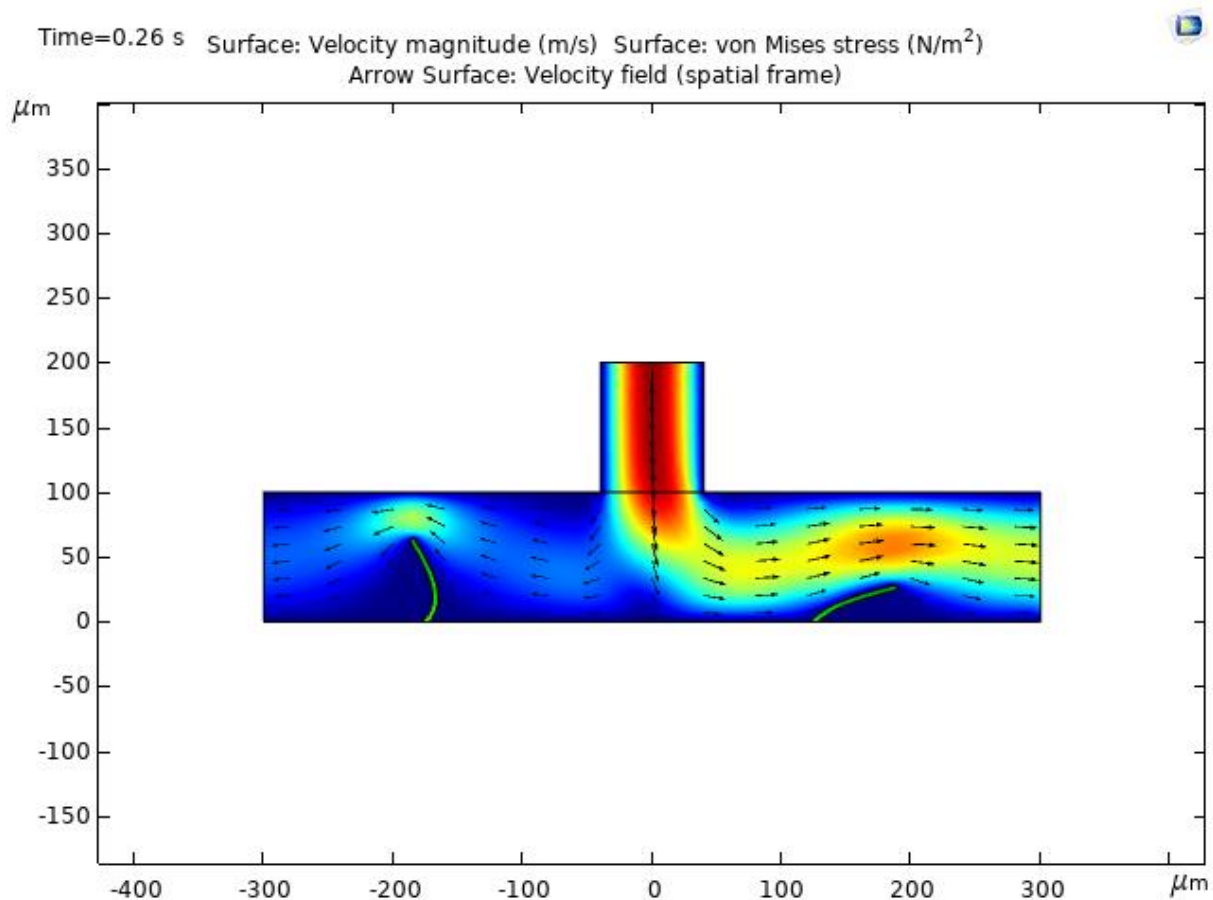


Figure 4-10: Velocity magnitude and velocity field, along with the von mises stress within the flaps during the pumping down-stroke.

Whereas, when fluid is drawn from the channel into the vertical chamber, the flaps are bent in the opposite directions, showing the solution at 0.74 s (see Figure 4-11). Now the right flap restricts the flow more than the left flap and the most of the fluid that is drawn into the chamber is from the left outlet. Thus, a net flow rate from left-to-right is achieved. This result has many applications, such as delivering fluid from a droplet reservoir connected to the left outlet into a microfluidic pathway connected to the right

outlet. Instead, creating a circulating system where a fluid is pumped around a continuous loop to cool a microelectronic system [71].

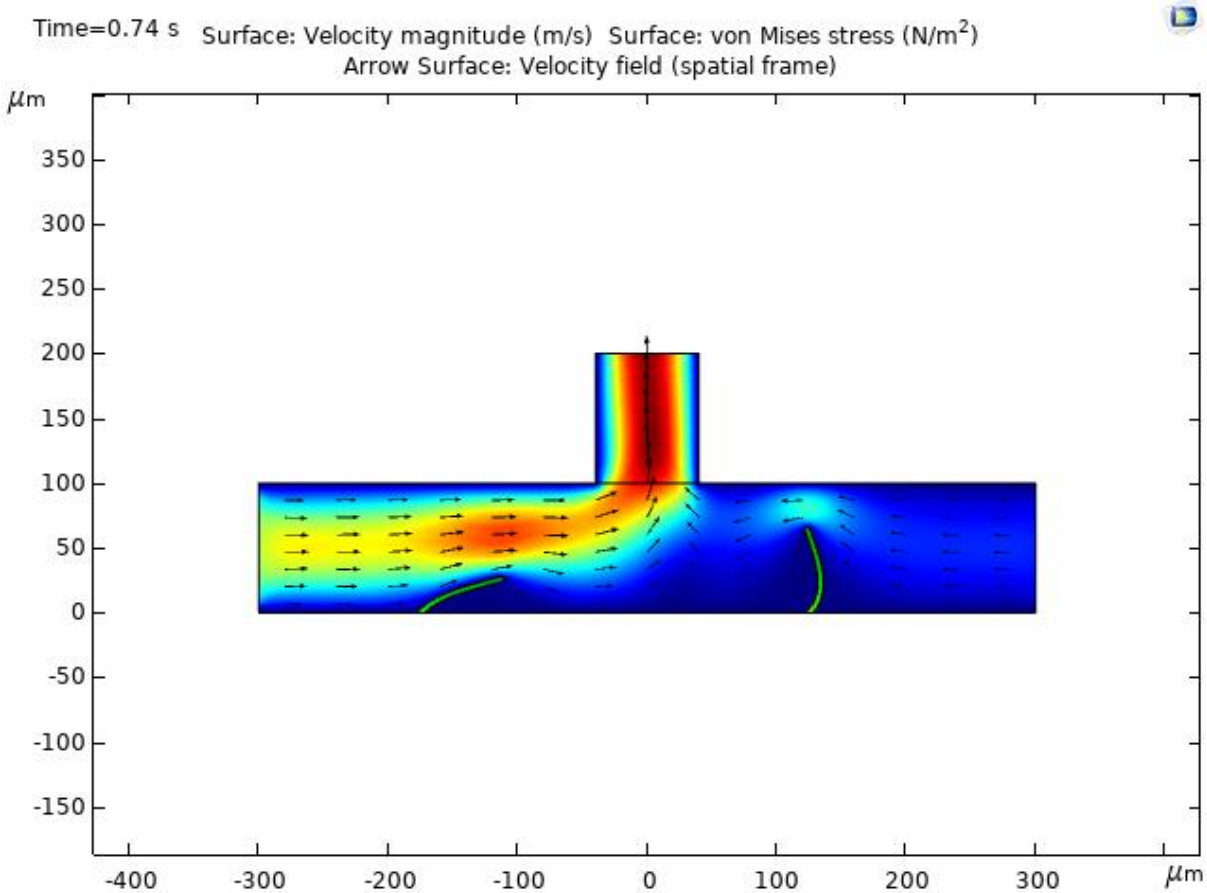


Figure 4-11: Velocity magnitude and velocity field, along with von mises stress within the flaps, during the pumping upstroke.

Figure 4-12 shows the fluid net volume that is pumped from left-to-right. The curve gradient (the net flow rate) varies sinusoidally with a period equal to the inlet velocity. The maximum gradient appears at intervals of odd multiples of 0.5 s, correspond to the peaks in the inlet velocity magnitude [71].



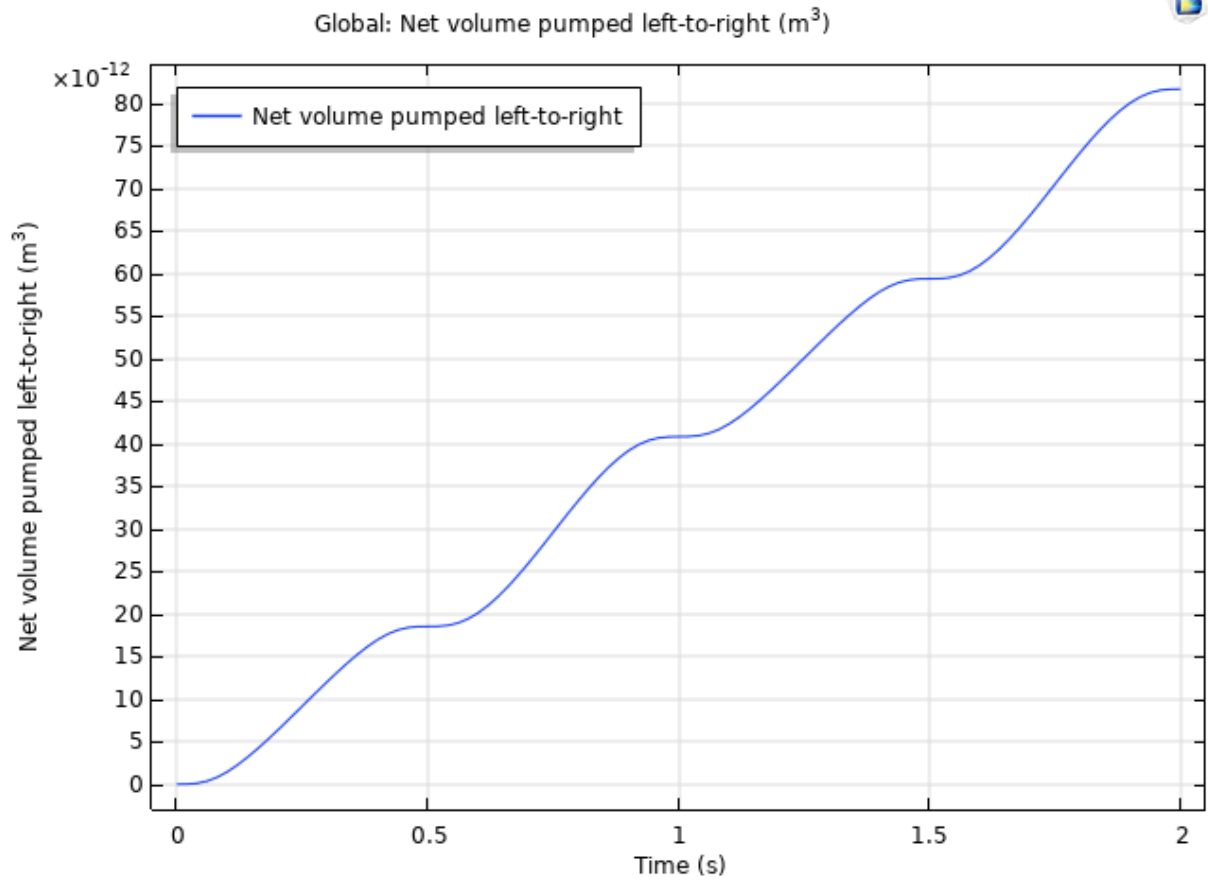


Figure 4-12: Effective volume pumped from left-to-right as a function of time.

## General Conclusion

This master's work consists of studying the functioning of a Micropump based on an MNP-Polymer membrane in order to develop Lab on chip and microfluidic application.

First, we started with a literature review of microfluidic citing their types devices and application. Next, we defined the polymer the most material used in MEMS and microfluidic devices.

We modeled a membrane made of MNP-PDMS composite and implemented this model on COMSOL Multiphysics digital simulation software based on the finite element method. Comparisons between the 0 and 5 wt. % particles loading into the membranes showed that the increase in Magnetic content improve the deflection of the membrane, in the other hand the addition of rigid particles within PDMS polymeric matrix hinders its deformation upon the effect of the external field. Consequently, the optimal performance of the composite in this case choosed the concentration of MNP's in Polymer to be 3%. Adding a dispersed phase into PDMS matrix causes the agglomeration of the MNP, which decrease the magnetic responsivity of the membrane. In addition to MNP's concentration and cluster effect, the dimension of the membrane can affect the deflection under the magnetic field.

Micropump mechanism model simulates the mechanism of a valves micropump, that is designed to be effective at low Reynolds numbers, overcoming hydrodynamic reversibility.

This work should be continued to know the feasibility of such micropump, by study the behavior of the composite membrane in the frequency domain, also the time dependent study should be done, to know the response time of membrane under a magnetic field, which is very hard because we used a very weak computer.

This theoretical work is based on several approaches, in order to get more precision, we should do the experimental tests.

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