# B. TECH. PROJECT REPORT

**On**

# Design and Development of a Peristaltic Pump


BY

**Taha Khan**

**DISCIPLINE OF MECHANICAL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY INDORE**


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# Design and Development of a Peristaltic Pump

**PROJECT REPORT**

*Submitted in partial fulfillment of the requirements for the award of the degrees*

***of***

**BACHELOR OF TECHNOLOGY**

**in**

**MECHANICAL ENGINEERING**

*Submitted by:*


**Taha Khan**
**Discipline of Mechanical Engineering**


*Guided by:*


**Prof. Shanmugam Dhinakaran (IIT Indore)**


**INDIAN INSTITUTE OF TECHNOLOGY INDORE**
**May 2022**

## CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Design and Development of a Peristaltic Pump"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering' completed under the supervision of **Prof. Shanmugam Dhinakaran,** Professor, Discipline of Mechanical Engineering, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

**Taha Khan**
**180003058**

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## CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the student is correct to the best of my knowledge.

May 27, 2022

**Prof. Shanmugam Dhinakaran**
**Professor**
**Department of Mechanical Engineering**
**IIT Indore**

# PREFACE

This report on “**The Design and Development of a Peristaltic Pump”** is prepared under the guidance of Prof. Shanmugam Dhinakaran.

*Through this report, I have attempted to study the construction and flow characteristics of peristaltic pumps, and to verify these findings experimentally in order to support the existing literature and highlight the advantages of using this device relating to the ease of manipulating flow rate and precision.*

*Through this thesis, efforts have been made to present the methodology, results and conclusions of the study in a lucid and comprehensible manner.Figures, graphs and tables have been included to make the content more illustrative.*

**Taha Khan**
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

# Acknowledgements

I wish to thank Prof. Shanmugam Dhinakaran for his kind support and valuable guidance. He enabled all of my ideas to take shape into this project and supported me in the completion of the objectives. I am really grateful for the opportunities I received under his tutelage.

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**Taha Khan**
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

Abstract

Pumps are used in nature and engineering for a variety of purposes, such as the transportation of several fluids, particles, and mixtures. Peristaltic pumping is one such form of fluid transport which occurs when a progressing wave of tube contraction or expansion travels along the length of a flexible tube containing a fluid, and by extension, peristaltic pumps are positive displacement pumps used in liquid transport. These pumps have the advantages of not contaminating the carried liquid, their fabrication is not demanding and they prove convenient for the transport of shear-sensitive and abrasive fluids. The aim of this project is to review and summarize the most important properties of these pumps, followed by an analytical analysis of the flow characteristics within these pumps and finally to carry out an experimental verification of these characteristics. A literature review of relevant work provides an understanding of the construction, basic principle of working and pump design methodologies of different types of peristaltic pumps. The advantages and critical applications are also discussed. The literature on the fluid flow analytics of peristaltic pumps is also studied. This study goes over the nature of flow within peristaltic pumps, the mathematical reasoning behind peristalsis and the various structural and environmental factors which affect the nature of the flow, as well as the reasons which motivated this research in the first place. In order to further explore and confirm these flow characteristics, an experimental analysis is conducted. The review of the construction and applications of peristaltic pumps aids in selecting an appropriate pump for the required analysis. The operation of the selected pump is observed and evaluated. The reliability and precision of the pump in non-continuous operation mode is also tested. A reprogrammable capability is provided to the pump in order to vary the delay between continuous ejections based on any required dosing precision.

**Keywords:** Peristalsis, Microfluidics, Pump Design, Flow Characteristics

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# Chapter 1

# Introduction

Peristaltic pumps are positive displacement pumps used for the purposes of fluid transport for a wide variety of applications. These pumps do not contaminate the carried liquid, their construction is not demanding and they prove convenient for the transport of aggressive and shear-sensitive liquids. Through their wide array of uses, there are many different types of these pumps based on their unique needs, such as requirements of high pressure, tube longevity, or low deviation in pressure.

This definition of a peristaltic pump can be broken down as follows:

1) Micro-pump:

   Micro-pumps are devices that can control and manipulate small fluid volumes.

2) Positive Displacement Pump:

   In these pumps, there are present either one or multiple movable boundaries which apply force upon the enclosed, fluid containing volumes, and this addition of energy leads to a rise in the pressure. This pressure can be increased up to the desired value such that it reaches the required valves or ports and flows out through the outlet. Examples of these pumps include peristaltic pumps, check valve pumps, valve-less rectification pumps and rotary pumps.

   These pumps are differentiated from dynamic pumps, in which addition of mechanical energy is a continuous process, leading in an increase in pressure at the outlet of the pump.

3) Peristalsis:

   Peristalsis is defined as the peculiar worm-like wave motion of the intestines and other hollow muscular structures. This phenomenon works due to the muscle fibres of the walls producing successive contractions, allowing their contents to be pushed forward.

Peristaltic pumps are used commonly to pump either clean and sterile fluids or chemically reactive fluids since these fluids are not exposed to contamination from contact with the pump components. Typical applications of peristaltic pumps include pumping IV fluids through an dosing device, apheresis, abrasive chemicals, solids slurries, and other materials where concealing the product from its surroundings is of utmost importance.

Controlled microscale movement of fluids is becoming increasingly important as genomics, proteomics, and the development of new medications gain traction.

## 1.1 Problem Definition:

The project is based around the growing research on peristaltic pumps, their various applications and their flow characteristics. Peristaltic pumps have been shown to be useful in a wide variety of fields, and there are many ways to go about implementing one such pump. These different types of pumps have their own sets of advantages and disadvantages.

Outside of practical implementations of these pumps, a vast amount of research is also focused on the nature of the flow within these pumps. These studies are concerned with the nature of the forces responsible for the working principle of peristalsis behind these pumps. Such studies also give way to suggest innovations in peristaltic pump design.

**Aim:** This project is concerned with studying the design and structure of the various types of peristaltic pumps currently being researched and produced, to study the flow characteristics within these pumps and finally, to confirm these flow characteristics using an appropriately selected peristaltic pump for experimental analysis.

**Objectives of the project:**

- To perform a thorough Literature Review on the ongoing and completed research work in the realm of peristaltic pumps.
- To study the literature on the analytical fluidic motion solutions within a peristaltic pump.
- To select and procure a peristaltic pump which meets the specific requirements of the experiment to be conducted.
- To study the flow characteristics of the chosen peristaltic pump as well as explore both continuous and intermittent flow.

## 1.2 Structure of the Document:

The report document is organized in the following main parts:

**Chapter 1** is the Introduction of the document and introduces the idea behind the project as well outlines the steps taken to complete it.

**Chapter 2** consists of the Literature Review done to establish an understanding of the concepts pertinent to the study.

**Chapter 3** is concerned with a review of Analytical Research Literature based on the flow characteristics in peristaltic pumps.

**Chapter 4** deals with the Design Principles behind peristaltic pump construction which helps us choose an appropriate pump for experimental analysis purposes.

**Chapter 5** establishes the details of the Experimental Analysis performed to verify the flow characteristics of our pump as well as examine its precision fluid handling.

**Chapter 6** is a repository of all the results and attempts to succinctly describe each result obtained over the course of this project.

**Chapter 7**, the final chapter of the thesis, draws insights from the conclusion of the experiments and describes the impact of the findings.

## Chapter 2

# Literature Review

Peristaltic pumping is a form of fluid transport that occurs when a progressive wave of area contraction or expansion propagates along the length of a distensible tube containing a liquid.

Physiologically, peristaltic pumping is an inherent neuromuscular property of any tubular smooth muscle structure. The body uses this phenomenon to propel or to mix the contents of a tube, as in the uterus, the gastro-intestinal tract, the bile duct, and other glandular ducts [1].

Roller (or finger) pumps also operate on the principle of peristalsis. In these pumps the tube acts as a passive component but is compressed either by rotating rollers, by an array of mechanical fingers or by a nutating plate. These devices find uses in the pumping of fluids such as blood, foods, corrosive fluids and slurries whenever it is required for the delivered fluid to avoid contact with the physical components of the pump [2].

Typically, the compression rollers or fingers occlude the tube completely (that is, cover the entire width of the tube) or almost completely, and the mechanism, via applying compression to produce positive displacement, “milks” the liquid through the tube. Viscous forces, on the other hand, can provide efficient pumping despite the lumen of the tube being blocked, but the flow rate is then determined by the pressure head.

### 2.1 Basic Mechanism of Peristaltic Pumping:

Let us take a basic peristaltic pumping system, which consists of a long tube closed at both ends and a peristaltic wave of contraction is produced moving to the right at speed c.

In the wave frame of reference, assuming that the flow is viscous and inertia free, the velocity profile in the compressed section must be parabolic, with velocity –c at the walls. As we move from the right to the left inside the compressed region, the pressure gradually decreases due to viscous losses. Moving to the laboratory frame, it is clear that the same pressure gradient exists, which means that the travelling peristaltic by virtue of its existence creates a rising pressure gradient in its direction of motion.

Were we to remove the end closures, an additional flow would be induced depending upon the pressures imposed. This means that the fluid will now flow to the right in the expanded regions and the flow to the left in the compressed regions will be reduced as compared to the case without the end closures.

Two important conclusions can be drawn from this simple model:

1) Dissipation effects are essential for the functioning of peristaltic pumps. The viscous effects are directly responsible for the pressure drops in the contracted sections.
2) The fluid in the compressed regions moves in a direction opposite to the wave direction while the fluid in the expanded regions moves in the same direction as the wave.

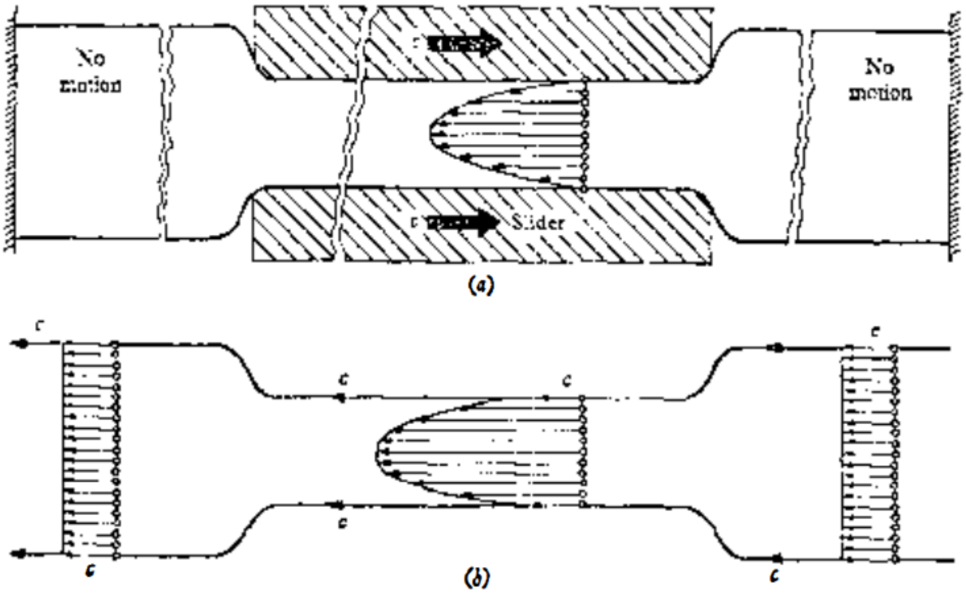


*Figure 1. Conceptual illustration of Peristaltic Pumping. Upper: unsteady flow in laboratory frame, Lower: steady flow in wave frame [2]*

## 2.2 Structure of Peristaltic Pumps:

Peristaltic pumps emulate the biological process of peristalsis, so the structure of a peristaltic pump is designed to emulate the contraction of smooth muscles in rhythmic waves [3]. Peristaltic pumps can be broadly classified into two types:

1) Rotary Peristaltic Pump:

Rotary peristaltic pumps usually involve a set of revolving mechanical protrusions which compress a tube and thus create a travelling peristaltic wave. The number of these mechanical protrusions may vary. The protrusions may either roll or slide along the length of the tube.

The size and composition of the tube may be adjusted to accommodate different fluid types, or to manipulate the flow rate. The flow rate can also be changed by adjusting the rotation rate and changing the direction of the motor activation applies a reversing effect on the fluid flow direction. Since the fluid always stays within the confines of the tube, it never comes into contact with any of the pump elements, which means both that the fluid stays uncontaminated and that the tube is protected from corrosion or abrasion by high shear fluids. The replacement of the tube is also an easy and convenient process.

2) Linear Peristaltic Pump:

Linear peristaltic pumps contain an array of piston actuators which sequentially compress a distensible tube. The above discussed features of macroscale rotary pumps are also found in the application of microscale linear pumps. Linear peristaltic pumps provide an accurate flow rate control and are thus applicable whenever this property is required (such as drug delivery). The number and types of these actuators vary greatly.

In both cases, a traversing peristaltic wave positively displaces fluid and produces a flow, which firmly places peristaltic pumps under the category of positive displacement pumps. It is also noted that the flow rate can be manipulated in both cases by increasing the tube diameter and increasing the pumping cycle frequency respectively.

## 2.3 Advantages of Peristaltic Pumps:

The biggest benefit of peristaltic pumps is the cleanliness provided during fluid flow. The fluid is always restrained to the inside of the tube and does not come into contact with the pump components. Also, cross-contamination between fluids can easily be avoided by replacing the tube.

The flow rate of the pump can be adjusted to provide a gentle pumping action, which makes it suitable for the transport of delicate fluids such as reactive liquids and cell suspensions. In addition, peristaltic pumps may have the property of being self-priming. This feature is achieved because of the low pressure region being left behind by the travelling peristaltic wave. Also, the flow direction in the pump can be reversed by simply changing the rotational direction of the pump. Rotary peristaltic pumps for the most part find use in macroscale applications while opportunities for using linear peristaltic pumps are mainly restricted to niche applications, for e.g., intravenous drug delivery.

On the microscale, the advantages obtained due to cleanliness and ease of changing mechanical components are insubstantial. Therefore, use of peristaltic micro pumps must be justified for other reasons. Both self-priming and bi-directionality are still attractive features that are valid on the microscale, but the biggest benefit is the simplicity in design.

A possible actuator for a peristaltic pump is any mechanism that changes the volume of a chamber or channel. A typical active micro valve, for example, has a membrane that may be pushed against a seal to close it or withdrawn away from it to open it. To make a linear peristaltic micro pump, two or more active micro valves can be arranged in a series and operated with the necessary phasing. Peristaltic pumping principles apply to liquids and gases, and micro pumps for both have been shown [3, 4, 5].

## 2.4 Progression of Peristaltic Pump Design:

Various iterations of the pump have been constructed and tested over the years. These include miniature peristaltic pumps which use a single reciprocator actuation motion to produce pumping. Pumping is achieved via the upstream valve as it compresses a section of the tube. Such a pump does not produce a continuous outflow of fluid, since only a compressive stroke of the tube takes place [6].

A peristaltic pump was created which suggested that a housing should be fabricated to contain a distensible tube. The housing would have curved walls and a clamp to restrict the tube in position. It would contain a compression roller assembly including at least one guide roller. A set of guide rollers would be peripherally spaced between compression rollers which come into contact with the flexible tube during rotation of the roller assembly. The pump utilized a gear system for rotating the rollers [7].

A peristaltic pump was designed which consists of a channel in a frame member adapted to receive and house a peristaltic tube, a flexible peristaltic tube fitted into said channel and containing in addition an opening for the inlet fluid to be allowed in as well as a rotary carrier mounted concentrically with said channel [8].

A novel PDMS (Polydimethylsiloxane) and tubing-based micro pump was presented based on direct actuation. It consisted of a PDMS microchip which was pumped peristaltically, and it contained a circular hole in its center around which was constructed a micro channel. In this center hole, a motor driven roller type actuator was placed. This rotor applied force upon the channel walls as it rotated, resulting in peristaltic motion [9].

A similar actuator was utilized to construct a miniature peristaltic pump, in which the housing was made up of a polycarbonate substance and the housing was adapted to fit commercial tubing.

## 2.5 Rotary Peristaltic Pumps:

Rotary peristaltic pumps consist of a pump case, a hose, a rotor, a shoe and a motor. The pump case houses the rotor that lays down at upon the shaft, which supports it. Normally at least two shoes will be present at the edges of the rotor. This flange will be connecting the input and output fluid reservoirs [10].

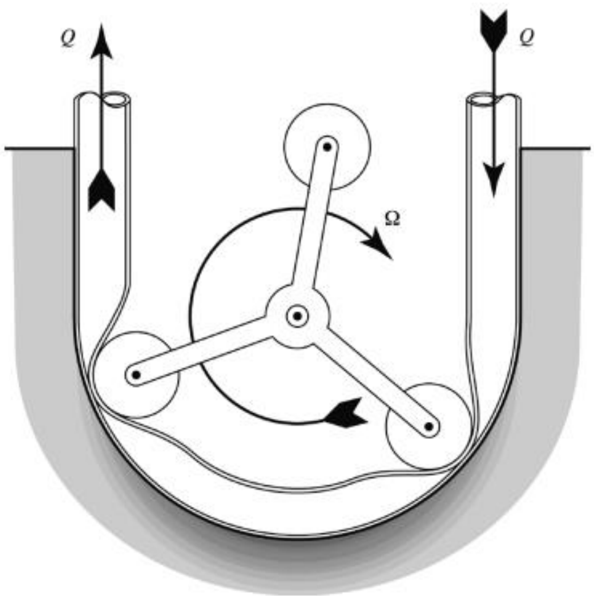


*Figure 2. Rotary Peristaltic Pump [3]*

At the start of the pumping sequence, the first roller blocks the inlet of the tubing. As a consequence, the roller moves forward and pushes the tube segment to the manifold. Hence, it pushes the fluid inside the tube forward, creating a 'milking' motion. The other roller closes the tube inlet before the first roller reaches the outlet, and this helps minimize the backflow. The next roller is now responsible the successive pressure wave as the first roller leaves the outlet [11].

Rotary peristaltic pumps can further be categorized based on particular criteria. One of the most important criteria of distinction is characterized by the tubing. Using this criteria, two types of pumps can be differentiated: the tube pumps and the hose pumps:

1) **Hose Pumps:** As the name suggests, hose pumps contain a reinforced tube as the tubing system, which is termed the 'hose'. Hoses require greater forces for compression and as such need bigger and stronger motors to produce equivalent flow rates. This also makes hose pumps more expensive in fabrication and operation. The ability of hose pumps to operate against bigger against higher pressure gradients compared to tube pumps is their main advantage. [11].

2) **Tube Pumps:** Tube pumps contain polymers such as PVC, silicon or fluoropolymers as the tubing material. These types of peristaltic pumps are the most commonplace these days. Additionally, the differences between tube pumps and hose pumps are melting as materials continue to improve in quality. Tube pumps have the disadvantage of being able to operate only under low pressure gradients, however, they need smaller motors and forces to function. So, they have the advantage of being cheaper and space-saving [12, 13, 14].

Another criterion for classifying peristaltic pumps is based on the type of propulsion. Modern rotary peristaltic pumps for the most part contain a central rotor and connected to this rotor are multiple rotors. These rollers are responsible for pressing the lining of the tube and thus propelling the fluid forward, as well as preventing leakage.

Another type of pump involves a singular rotor. Termed the '360-degree peristaltic pump', such pumps are rare as rotary pumps generally involve at least two rollers. In some cases, one of the two rollers takes the role of only preventing back flow and has no responsibility in providing forward fluid movement [15].

As the number of rollers increases on a rotary pump, it becomes possible to generate more pressure waves in the same amount of time and thus decrease the deviance of pressure on the output. This however also means that the lifetime of the tube lining is reduced [16].

The third criterion for distinguishing pumps is the way the rollers are fixed.

1) **Fixed occlusion:** This is the simplest method of roller fixing. The rollers have a fixed locus, that is, they keep a constant distance from the tube at all times. This method proves simple in implementation, robust as well as undemanding. However, since it depends on the wall thickness, the tube lifetime does suffer [17].
2) **Spring loaded rollers:** In these types of pumps, the rollers are mounted on springs. As such, the rollers are able to keep a constant pressure on the tube. Since now the pressure does not depend upon the wall thickness, spring loaded peristaltic pumps boast a longer tube lifetime, constant pressure as well as the availability to accommodate a variety of tube sizes. While the structure of these pumps are generally symmetric, some cases of asymmetric spring loaded pumps exist which have been shown to have increased lifetime and stability [18].

*Advantages of rotary peristaltic pumps: [19, 20, 21]*

1) Since the pumps are driven by compression of the tube, the fluid being pumped will never come into contact with the pump mechanism itself and thus remains uncontaminated. In addition, the pump mechanism does not need frequent cleaning. As the fluid does not leave the tubing, these pumps are incredible resistant to abrasive and reactive fluids.
2) Peristaltic pumps are self-priming, that is, they do not need any specific action for priming. They are also immune to dry running since the fluid does not play the role of a lubricant in the pump, and so the instrument is not damaged if run empty. These pumps also boast the absence of any valves and seals, making them very easy to maintain.
3) They have the capability of operating against other pumps reversibly. Multi-channel systems can also be built easily.
4) The suction height for peristaltic pumps is impressive, and no siphoning effect occurs if the pump is stopped mid-transport. The viscosity of the transported medium has little effect on the efficacy of the pump.

5) Since low shearing forces are present during the peristaltic motion, the pumps are ideal for transporting shear sensitive fluids.

*Disadvantages of rotary peristaltic pumps: [22, 23, 24]*

1) The replaceable tubing might be cause for deviations in the pump system, leading to regular calibrations to reach the desired accuracy.
2) As the tubing takes the brunt of the transported fluid's abrasiveness and reactivity, these tubes need to be changed and recalibrated regularly. If these tubes are not changed regularly and are used for extensive periods of time, they may get damage and cause leakages within the pump which might damage the mechanical components.
3) Due to the nature of the principle behind peristaltic pumps and specifically rotary pumps, some manner of pulsatile flow will be present within the pump. In addition, the flow rate is sensitive to any variation in the applied pressure gradient and their maximal differential pressure is lower compared to gear and piston pumps.

*Control of Rotary Peristaltic Pumps:*

**1) Control using Flow Meters:**

To establish flow control over peristaltic pumps, the most intuitive method is to measure the fluid flow at the outlet of the pump. Such a flow meter can be present within the pump system itself or it can be established separately. A variety of options are available for the type of controller and the flow meter type. The flow meter can be either be in contact with the transported fluid or it can measure the fluid flow by leaving it as is. Some examples of intact fluid flow meters include electromagnetic, doppler and optical sensors to determine the flow of the fluid. Open loop control is the simplest solution when using these methods. However, the known methods can be applied to design a closed loop control (e.g. PID control, robust control, etc.) [25].

**2) Control over the Pulsation:**

As seen earlier the pressure waves generated by the rollers cause the peristaltic pump to generate pulsation. The need for control over the pulsation to minimize it arises from some delicate systems which require a more stable flow, such as systems designed for chemical analysis. One solution available is to use a classical control methodology with a closed loop feedback system. Another solution is to increase the number of pump heads; this however would lead to a decrease in the tubing lifetime.

A unique solution the usage of an atrium. The atrium is a section of the tube with high elasticity. When attached at the outlet of the pump, it expands under fluid pressure and then gradually releases the fluid in a stable manner due to its elastic energy. As the name suggest, this idea is inspired by the functioning of the heart. A heavy disadvantage of this methodology is that the reduction in the pulsatile nature of the flow would be unpredictable and would depend highly on the material being used. [25]

**3) Repetitive Control:**

Periodical signals are dealt with in repetitive control. Its goal is to track and reject arbitrary fixed-period periodic transmissions. Periodical signals of varied frequency were also subjected to repetitive control. This means of control proves suitable for controlling peristaltic pumps in this manner. It has also shown to be promising in practice. [25]

## 2.6 Linear Peristaltic Pumps:

The structure of linear peristaltic pumps allows any actuator to be converted into a pump, which means that there is a lot of freedom and creativity in the design of these devices, as well as room for innovation.

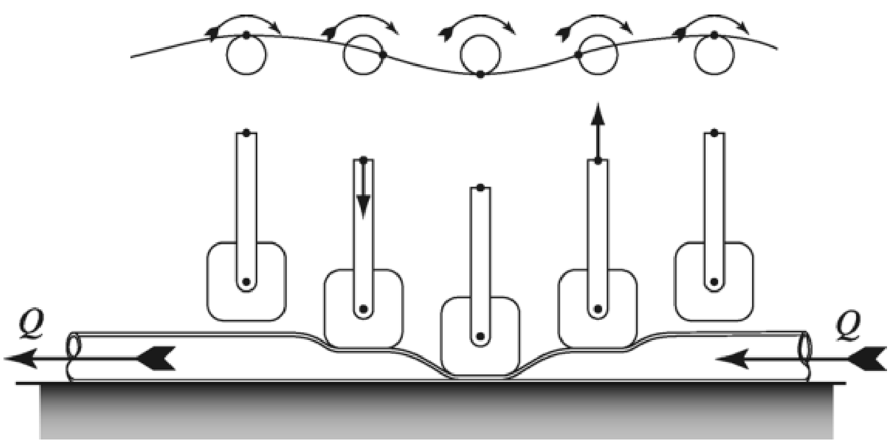


*Figure 3. Linear Peristaltic Pump [3]*

### *Key Terms associated with linear peristaltic pumps:*

When the pump is in the closed position, the volume enclosed within it is referred to as the dead volume. The difference between the dead volume and the volume in the open position is referred to as the stroke volume.

The compression ratio is the ratio of the stroke volume and the dead volume. Compression ratio plays an especially important role when it comes to pumping gases, since the compressibility of the fluid determines the amount of gas being released from the actuator. While this does not apply to liquids, the compression ratio is still useful in that it gives a measure of the severity with which bubbles impact the pump. Micro pumps can be classified on the basis of the actuators being used. There are external actuators, which are fabricated separately from the pump and attached later, and integrated actuators, which are fabricated alongside the other components of the microfluidic system. Both kinds of peristaltic micro pumps are equally common [4].

### *PDMS based Linear Peristaltic Pumps:*

A notable standout among linear peristaltic pumps are the colloidal peristaltic pumps. These consist of a suspension of colloidal silica particles which oscillate sinusoidally in a thin PDMS (polydimethylsiloxane) channel, which is externally actuated using a scanned laser performing optical trapping.

Peristaltic pumps based on PDMS have found wide application due to their ease of construction and versatility in functionality. The materials and processing tools required for the fabrication of PDMS are inexpensive compared to how semiconductors are typically fabricated in the industry. PDMS is compatible with biological systems, offers resistance to many abrasive chemicals, and its transparency to light makes it useful in chemical and biochemical analyses.

PDMS based actuators are constructed as follows: The fluid channels are placed between a thin PDMS layer and another substrate which can be either another PDMS layer or a glass or silicon layer. The actuator channels are placed in a thicker layer of PDMS at an angle of 90 degrees to the fluid channels. [27]

In operation, in order to close the pump chamber, an external source is utilised to inflate the actuator channels. The channel is restored to its original shape when the pressure is removed due to the natural elasticity of the PDMS. Since PDMS has a low modulus of elasticity, the pump chambers are sometimes designed to collapse completely when closed, thus allowing them to act either in isolation as pure valves or in concert for pumping. [26]

### *Linear Peristaltic Pumps Vs Passive Check-Valve Pumps:*

In a peristaltic pump, the phasing of multiple actuators is the only rectification means via which any fluid displaced by the working actuators is directed to the required direction of outflow. There are various other means of redirecting flow which are utilized by other pumps.

A passive check-valve pump consists of, as the name suggests, two passive, one-way check valves which contain some moving components. One of these valves is placed at the inlet and permits the fluid to enter the pump as the pump chamber expands, but prevents it from leaving during pump contraction. Similarly, another passive valve is placed at the outlet to prevent back flow during pump expansion, but to allow the fluid to exit during contraction. [28]

Valve less Rectification Pumps are alike, except that they replace the function of passive check valves with flow diodes. These flow diodes are nozzle or diffuser like structures containing no moving parts, but still displaying a preferred flow of direction owing to their geometry. [28]

The reason for comparison between these pumps and linear peristaltic pumps, is that they use only a single actuator while a peristaltic pump requires multiple (at least two) actuators to function.

One reason for preferring peristaltic pumps is that since they have no special fabrication or external connections, they can easily be integrated onto microchips. Electrostatically-actuated peristaltic micro pumps have been presented which are suitable for integration onto microchips. [29]

The fabrication process of peristaltic micro pumps is much less complex than that of passive check valves. They are also much less susceptible to fouling by bubbles or particles. While valve-less rectifiers are simple to fabricate and are not easily fouled by particles, they tend to have a larger footprint than peristaltic pump design.

In addition, peristaltic pumps can easily be made to flow in forward or reverse direction by changing the actuator phasing sequence. Such bidirectional flow capability is not easily realized in valve-less rectifiers and check-valve pumps.

*Actuator Types and Fabrication Materials:*

Materials which are commonplace in the fabrication of most microfluidic devices are also the first choices when it comes to constructing peristaltic pumps. Silicon and glass devices make use of thermopneumatic, piezoelectric, and electrostatic actuators.

PDMS peristaltic micro pumps make use of only pneumatic actuators. Plastic and mixed-type devices function using thermopneumatic, electrostatic and pneumatic actuators.

Some novel actuation methods of peristaltic pumps include:

1) Optically actuated colloidal silica spheres were the basis for a reported travelling wave pump. [26]
2) A piezoelectric silicon-glass device pumping water and air was reported by Husband 440 et al. (Microelectronic Engineering 73–74:858–863, 2004).
3) A magnetically driven PDMS pump for water was reported. [30]
4) Electrostatic pumps implemented in parylene for integration with μTAS devices were reported. [29]

## Chapter 3

# Analytical Study of Fluid Motions within a Peristaltic Pump

### 3.1 Preliminary review:

Research in peristaltic pumping was inspired by its possible effects on some phenomena concerning the ureter. Several models of ureteral function started becoming available as soon as accurate and reliable urometric measurements became available.

The earliest models were extremely idealized wherein the peristalsis was presented as an unending sequence of sinusoidal waves present in a two dimensional tube [1, 2]. A significant component of this research was the attempt at an explanation of the "reflux" phenomenon. The reflux phenomenon is responsible for phenomena such as bacteria sometimes travelling backwards from the bladder to the kidneys during ureteral flow, or similar movement in the small bowel. The phenomenon of diffusion was considered as a possible explanation, however, the rate of flow of these bacteria could not be explained by the same.

Later models did a better job of realistically portraying the peristaltic waves. The coupling between the dynamics of the ureteral muscle and the forces of fluid-mechanical origin were also studied. It was shown that observed urometric pressure pulses and flow rates could be accounted for by assuming internal dimensions of the ureter which seem physiologically plausible.

Contributions to the theory of peristaltic pumping were also made without any references to ureteral physiology [31, 32]. It was concluded that the time taken by chyme to travel the small intestine could be calculated and verified with high accuracy using the theory of peristaltic motion. The subsection of inertia-free long-wavelength theory of peristaltic pumping was useful in the study of the travelling wave geometry present in the tubes of roller pumps.

## 3.2 Parameters of Two Dimensional Peristaltic Flow:

A longitudinal train of progressive sinusoidal waves of traverse wall displacement in a plane two-dimensional channel is considered. One assumption of the problem is that the walls of the tube should move vertically only, which requires that the wall be extensible. An inextensible wall would invalidate the theory for flows of short wavelengths. [33]

In total there are four dimensionless parameters for the assumed flow. These are determined from the differential equation for the flow in the idealized model, the geometry of the model and finally, the boundary conditions of a specific problem. The parameters are as follows:

1) The Amplitude Ratio:

   $\varphi$, it gives a measure of the relative degree of geometric occlusion, or the squeeze. It should be noted that $0 < \varphi < 1$

2) The Wave Number ($\alpha$):

   The wave number is determined by the curvature and slope of the wall. In case the wavelengths are long, the curvature of streamlines becomes very small and the pressure is instantly uniform at any position in the tube consequently.

3) The Reynold number (R):

   The Reynold number in this case is defined as the correct ratio of inertial to viscous terms when the peristalsis acts as a pump and the inertial effects are relatively small.

   This parameter specifically is the cause for most interest due to the importance of viscosity in peristaltic pumping.

   The value of Reynold's number also characterizes the ratio of the vorticity diffusion time over the tube radius to the time period of the peristalsis.

   When the value of Reynold's number is infinitesimal, the flow has 0 inertial force and represents an instantaneous velocity profile that is Poiseuille-like.

   For values of Reynold's number which go to infinity, the velocity distribution is virtually uniform over any cross-section of the tube.

4) Either the dimensionless parameter of 'time-mean flow' or the dimensionless parameter of 'pressure rise per wavelength'.

## 3.3 Peristaltic Pumping at Low Reynolds Number and Very Long Wavelengths:

This particular case is solvable with a minimum amount of mathematics and thus presents an easy to obtain description of the characteristics of peristaltic pumping. In addition, comparing the results of these solutions with experimental data has revealed surprising amount of validity. [34, 35]

For this case, we have R = α = 0.

It is found that the local velocity profile is of parabolic nature. This can be explained as follows: The wave number being 0 implies that the curvature in the streamlines is non-existent and thus, there are no traverse pressure gradients, and the Reynold's number being equal to 0 suggests that the inertia is completely gone. These are the precise local conditions for Poiseuille flow.

It is also observed that wherever the tube has heavy contractions, the pressure gradients tend to be very high.

For all further calculations, it is assumed that the length of tube is an integral number of wavelengths, which satisfies the conditions for steady flow inside the wave frame. The succession of peristaltic waves can now be considered to be infinite in number, despite the length of the tube being finite, so long as the number of such waves is integral. This assumption also provides ease in dealing with the case of R > 0, that is, when the fluid inertia is not completely absent.

## 3.4 Pressure-Flow Characteristics:

In the wave frame, the flow is completely steady. As a result, the pressure difference between two points exactly one λ apart is constant. This pressure difference across one wavelength is denoted as ΔPλ.

Assuming the peristaltic wave shape to be sinusoidal, the following relationship is obtained between the flow rate (time mean flow) and the pressure rise per wavelength:

$$Q = \frac{3\varphi^2}{2 + \varphi^2} - \frac{1}{3\pi} \frac{(1 - \varphi^2)^{\frac{5}{2}}}{2 + \varphi^2} \, .\Delta P_\lambda$$

We see that the flow rate is a linearly decreasing function of the pressure difference. We can interpret this expression for the flow rate as a sum of two separate terms.

The first part of the expression can be interpreted as the fluid flow produced by the pump when there is no pressure gradient present. The second part represents the backwards "leakage" parabolic flow caused by the presence of the acting pressure gradient.

The pumping efficiency of the peristaltic pump reaches its peak at φ = 1, that is, complete occlusion, because at this point the second term of the expression, that is, the backflow, becomes null and the flow is governed completely by the positive first term.

*Pumping Range:* We can now define the pumping range as the range of flow in which both the pressure difference across a wavelength and the flow rate are positive. Its minimum value, Q=0 is achieved when the pressure gradient is maximum, and its maximum value is achieved when the pressure gradient becomes zero, that is, when there is no head difference across the pump.

Weinberg (1970) had carried out an experiment to verify the above relationship. [36]

## 3.5 Reflux:

A big reason for the research conducted in the field of fluid flow within a peristaltic pump was to explain the physiological concept of ureteral or gastrointestinal reflux. One version of the fluid flow equation for the velocity profile obtained is as follows.

$$\frac{u}{c} = \frac{3}{2H^3} \, (Q + H - 1)(H^2 - \eta^2)$$

Where η is the dimensionless tube radius, H is the dimensionless wave distance, c is the wave speed and u is the horizontal velocity.

So, at any cross section, the fluid moves alternatively to and fro at different positions with respect to the passage of the wave. This velocity profile alone however is not informative on whether a packet of fluid is generally moving with or against the peristaltic wave.

Lagrangian trajectories of the fluid particles were calculated and it was shown that near the axis of the tube, the fluid particles have a positive velocity regardless of the flow rate. This is to say, they generally flow in the direction of the travelling wave. On the other hand, fluid particles near the walls of the tube tend to have a net negative displacement for small values of Q and a net positive displacement for large values of Q.

Many such trajectory calculations have been conducted, all suggesting that near the walls of the tube, the fluid particles flow backwards as long as certain conditions are met. Unfortunately, according to some experimental tests performed on a physical ureter model, it was seen that these specific circumstances required for reflux do not occur in a normal ureter.

Even so, this technique of determining trajectories of individual particles at different locations in the cross-section to find the pre-requisite conditions for reflux was explored further.

It was noticed that as a consequence of the steady flow rate in the wave frame, the fluid particle trajectories overlap with the streamlines of the flow. Therefore, the stream function of the flow can be utilized as a means of identifying material particles. Using this, it was found that reflux occurs near the walls of the tube only when the flow rate for some particular streamline surpasses the value of the mean time flow at the wall.

Therefore, reflux occurs only when the fluid flow rate is less than a certain critical value, which itself is less than the maximum flow rate. [36]

## Chapter 4

# Design of the Selected Pump

## 4.1 Available Design Methods:

Peristaltic pumps for research at the laboratory scale are available from a variety of manufacturers such as Lambda, Fisher Scientific, and MEINHARD. These commercial pumps generally fall into two categories:

1) Extremely precise pumps that have a limited maximum flow rate
2) Less precise pumps that may pump a broad range of flow rates.

Pumps are available at resolutions as low as 0.2 µL/min, however, the flow rate of these pumps peaks at about 60 µL/min. Pumps in the range of a 1 µL/min resolution have the ability to achieve flow rates as high as 50 mL/min.

Rapid prototyping techniques such as 3D printing can also be used to build peristaltic pumps in-house. Several designs for open-source 3D printing peristaltic pumps have previously been demonstrated in studies. Many of these designs rely on a single big roller to stretch many tubes. Multi-channel pumping is possible, but all pumps will have the same flow rate. This may be useful for assays in which numerous tests are run at the same time, but it suffers from the inability to control each flow separately. [37]

Some of these 3D printed pumps employ more widely available Fused-Filament Fabrication (FFF) 3D printers, however they face some problems, namely poor resolution of printed components and anisotropy of part strengths. Other designs use resin-based 3D printing to avoid the problems associated with FFF 3D printed parts. SLA (resin-based stereo lithography) is more accurate than FFF 3D printing.

Masked stereo lithography, or mSLA, is the most popular type of SLA 3D printing. This less frequent approach, on the other hand, faces different obstacles than FFF 3D printing. In comparison to FFF thermoplastic, mSLA requires the use of hazardous resins, which are both dirty and more expensive. Resin-based 3D prints must additionally be cleaned with isopropyl alcohol before being UV-cured. [38]

This additional step in the workflow is not necessarily a problem, but it adds additional complexity and workspace to handle the hazardous resin. Parts that are made via mSLA demonstrate a higher resolution and improved isotropy over parts made with FFF.

Pumps made using FFF methods typically include a gear reduction to offer greater torque to move the rotors and are not capable of extremely low flow rates, according to one apparent pattern. Pumps made using mSLA, on the other hand, can typically drive such low flow rates without the use of extra hardware such as ball bearings. A thread form or a threaded insert may be cut or inserted in FFF pieces to enable for uniform and dependable fastening. Because the photopolymer resin used in mSLA is brittle and inserts cannot be melted in, adding fasteners to these prints necessitates a more deliberate design procedure. [39]

## 4.2 Effects of Occlusion:

The modest flow rates required to reduce backpressure at the micro fluids scale make macro-scale hardware for micro-scale fluids difficult to create. Surface tension is a fundamental determinant of fluid behavior in a slow flow regime. Furthermore, as the length of tubing and the square of the fluid velocity rise, the resistance to flow increases dramatically.

Pressure drop in micro channels in routine tests can be very high due to their incredibly small diameter. Micro channels have such a high relative surface roughness that continuous flow is severely hindered by the back pressure of the channels. As a result, the majority of microfluidic analysis takes place in the laminar or creeping flow areas. Manufacturing tolerances on peristaltic pumps play an essential role in these flow regimes, since if the occlusion of the pump is too low, fluid can flow backwards through it. The gap between the two walls of the tube when it is compressed is the occlusion of a peristaltic pump.

A zero or low occlusion pump will produce a higher output pressure but will shorten the life of the tubing. Higher occlusion pumps will reduce tubing wear while allowing flow to pass back through the pump. [40]

## 4.3 The Chosen Pump:

The system fabrication of the pump can be considered to be made up of two main subsystems: the DC power supply, the Arduino and the L298N Motor Driver are contained in the electrical subsystem, and the mechanical pump itself which is assembled with basic hardware.

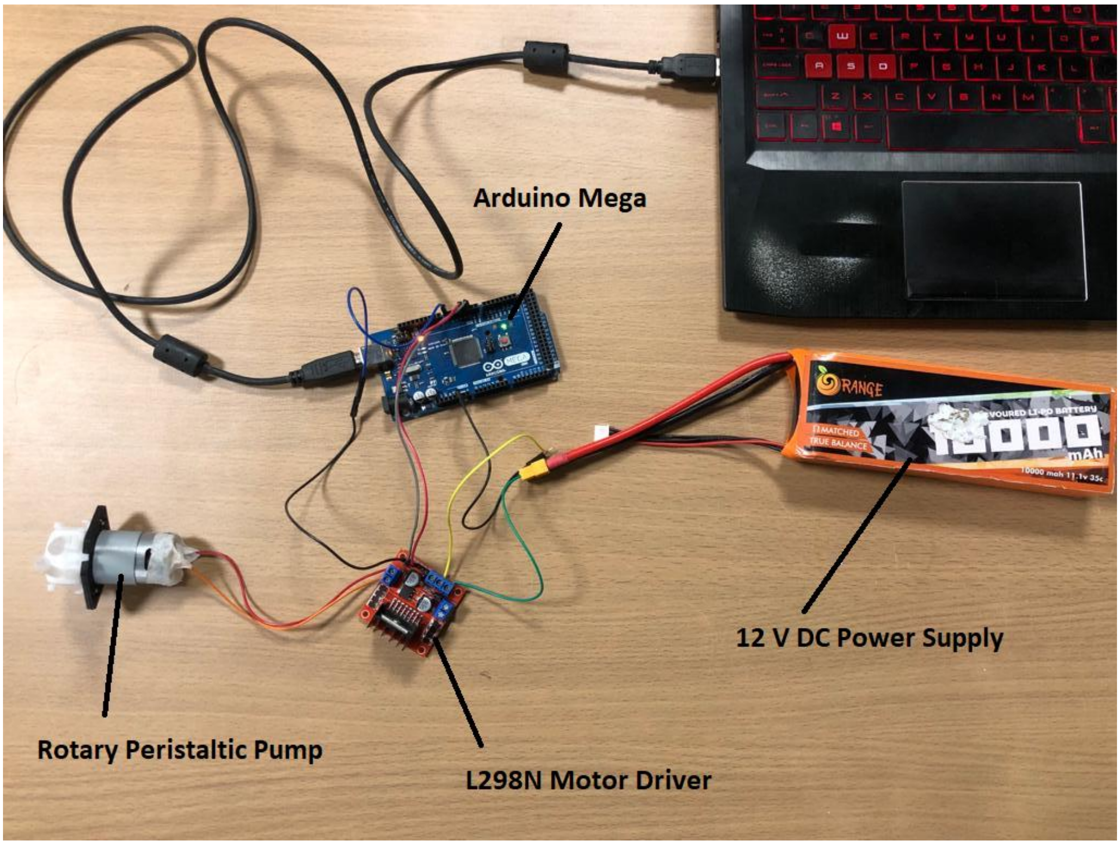


*Figure 4. Complete Peristaltic Pump Experimental Set-Up*

An Arduino board acts as the programmable interface of the pump. It is programmed using the free Arduino integrated development environment (IDE) via a USB connection to a personal computer. This prototyping platform can send programmable direction and step instructions to the motor driver, which in turn is responsible for controlling the rotation speed and direction of rotation of the pump rotor. The DC Motor transmits power to the pump via the rotor. The pump is placed on top of this motor. It can be considered to be made up of two main units, the rotor and the stator. The rotor body consists of three cylindrical elements, which are attached on top of it placed side by side in a triangular arrangement. These elements act as the rollers of the pump, and are responsible for the peristaltic pumping action.

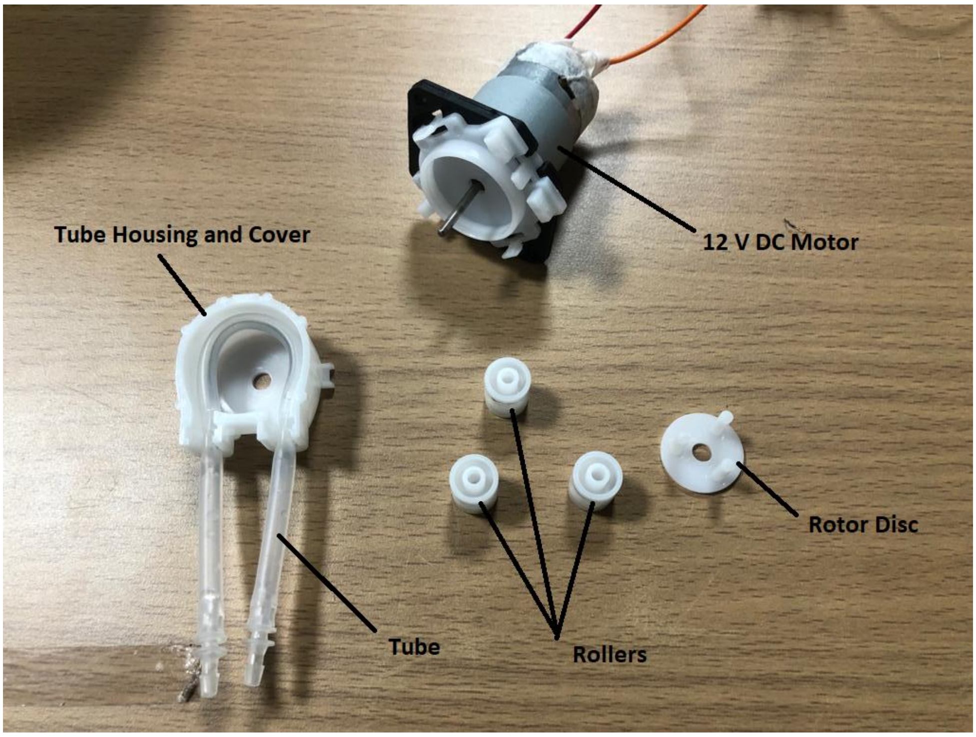


*Figure 5. Components of the Rotary Peristaltic Pump*

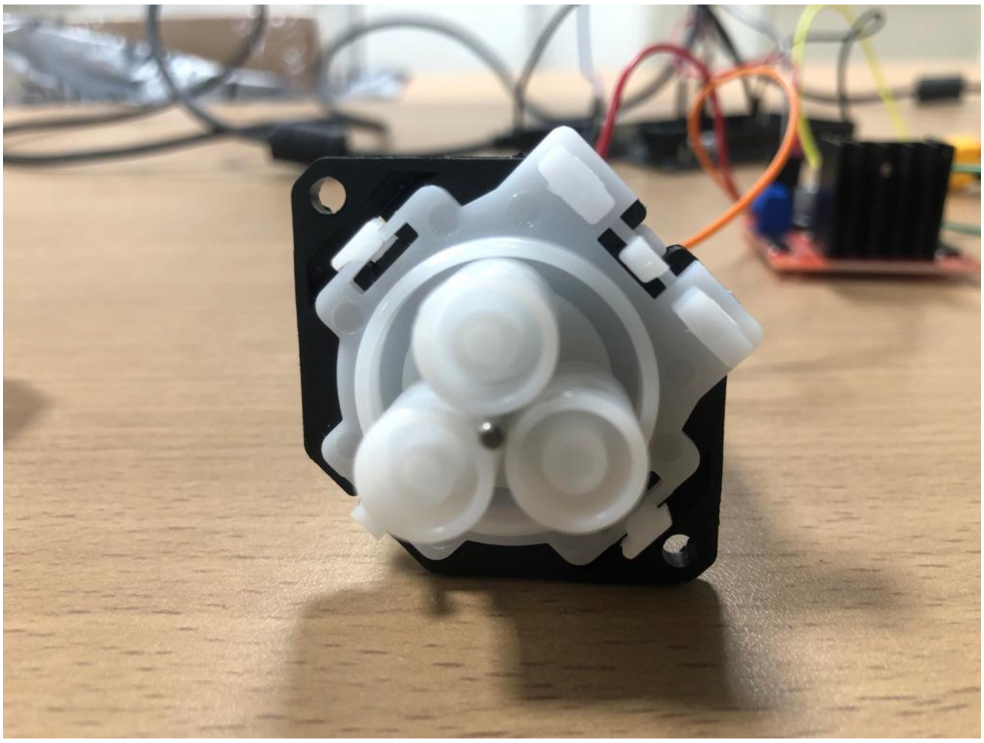

*Figure 6. Fitting the 3 Rollers over the Rotor and the DC Motor*

The stator is made up of three components, the base which contains the housing for the tube and two additional clamps to restrict the movement of the tube within the housing. The space between the rotor and the stator is completely occupied by the tube, so that it gets compressed against the stator when the rollers push against it. As the rotor is put into rotational motion, it presses up against the tubing and this cyclical compression is responsible for the pumping effect, as the requisite force is provided for driving the fluid through the tubing.

So all in all, the pump consists of the following components: 3 rollers, a rotor disc, the stator, the tubing and a 12 V DC Motor. The rotor is mounted directly to the faceplate holes of the motor, and the shaft for the rollers are pressed directly into it.

An alternate design utilized fixed steel pins to press against the tubing to produce the needed flow for pumping. However, this design was not a viable option as explained below. The friction between the pins and the tubing can be extremely high, which might cause the motor to stall at all speeds. When turned manually, the friction on the tubing also caused the tubing to be pushed out of the path of the pins. Finally, the small diameter of the pins caused pinching and wear of the tubing used for the pumping action. The larger diameter of the rollers causes the force of the roller to be spread over a larger area and eliminate any creasing of the tubes.

Due to the method of operation, peristaltic pumps are very resilient, and can pump extremely viscous liquids and slurries with fewer issues than syringe pumps. They can also pump an indefinite volume from any size reservoir. The trade-off of this flexibility, however, is that the flow is characteristically pulsatile. Rather than having a smooth and continuous flow, the rollers push the liquid in pulses that are approximately the volume of the tube between each roller. Peristaltic pumps may be configured in one of two ways: “open” flow, where liquids are pumped from a main fluid reservoir that may be refilled, or “closed” flow, where the liquid being pumped is recirculated. In the closed flow configuration, the outlet of the pump is connected to the inlet, with process tubing and equipment between the two.

Peristaltic pumps with microfluidic-level flow rates are used in a variety of applications, including biology, chemistry, pharmacology, and environmental research. In biology, micro pumps are frequently used in gene chips and capillary electrophoresis studies. In chemical synthesis, micro fluid pumps have become a common equipment. Microfluidic reactors are commonly used for research involving extremely reactive, toxic, or explosive intermediates because they are both faster and safer. Because of the reduced volume, these reactions can be completed without having potentially devastating consequences.

## 4.4 Electronics and Firmware:

Simple control of the pumps was desirable, and so for this reason, a combination of an Arduino along with a Motor Driver were the most obvious choice.

### Arduino:

The Arduino Mega platform was utilized for control and processing. Arduino is an open-source platform used for providing programmable control over electronic projects. Arduino is a combination of both a physical board (the microcontroller) as well as a piece of software, the Arduino IDE (Integrated Development Environment). The IDE can be run on a personal computer and is used to write and then upload code to the programmable circuit board, or the microcontroller.

The Arduino requires a power source to operate. It can obtain this power from a computer through a USB port connection. This USB connection is also utilized to upload code onto the board.

The Arduino also consists of several different kinds of pins. These pins are labelled on the board and each serve a different purpose. The pins being made use of in this specific application facilitate the following functionalities: GND pins for providing a Ground voltage, Digital Pins for reading and transmitting digital signals, Analog Pins for reading and transmitting analog signals, and PWM Pins which act as normal digital pins but have the ability to simulate analog output.

### L298N Motor Driver:

The L298N motor driver operates on the principle of dual H-Bridges. It allows control over the direction and speed of two motors at the same time. The specifications of the controllable DC Motors are that they need to have voltages between 5 V and 35 V, with a peak current of up to 2A.

The Motor Driver in conjunction with the Arduino is able to control the speed of the DC Motor by simply controlling the input voltage to the motor. One common method of doing this is by using PWM signals.

PWM, or Pulse Width Modulation, is a method which provides the ability to adjust the average value of the voltage going to an electronic device by turning on and off the power at a fast rate. The average voltage is dependent upon the duty cycle, which is the amount of time a signal is ON as opposed to OFF in a single period of time.

Since the L298N is a dual H-Bridge Motor Driver, it also provides the ability to switch the direction of the motor, and therefore the pump flow direction. An H-Bridge consists of four switching elements with the motor at center, thus forming an H-like configuration. If two particular switches are activated at the same time, the direction of current flow is changed and so is the direction of the motor.

The Enable A and Enable B pins of the motor driver are used for exacting control over the speed of the motor. Unless an Enable pin is activated, the motor will only work at maximum speed. The motor can be disabled by connecting this pin to the Ground.

The Input 1 and Input 2 pins provide control over the direction of rotation of the motor. In essence, these pins are responsible for controlling the switches of the H-Bridge inside the L298N IC. If Input 1 is LOW and Input 2 is HIGH, the motor will move forward and vice versa if Input 1 is HIGH and Input 2 is LOW. If both inputs are the same the motor will not work.

A main feature of the pump is that it is assembled with the availability of being reprogrammable, allowing operators to easily and quickly change the properties of the driven flow to match their needs. Peristaltic pumps find usage in fields of liquid metering, so the pump's capability to precisely and consistently eject aliquots of a fluid was examined.

## Chapter 5

# The Experimental Analysis

There is significance to understanding flow characteristics of a peristaltic pump for optimum design and usage. The design directions can be based on available knowledge and experience gained from experiments.

The flow characteristics have been known and studied in literature extensively, as was discussed in the literature review. However, a majority of such discussion is focused more on some of the most widely used commercial and industrial pumps such as centrifugal pumps. There is rare published information on experimentally studied flow characteristics of a peristaltic pumps, since it is for the most part limited to low pressure-rise applications.

In this experiment, two structural factors of the peristaltic pump: The tube size and the rotor speed are investigated experimentally on how they affect the flow characteristics.

A volumetric method of flow measurement was implemented for this study since the output flow rate is quite steady. It consists simply of measuring the time taken by a pump operating steadily to fill a vessel whose volume is fixed and measureable. The ratio of this fixed volume and time taken gives us the average pump flow rate.

To measure the effect of tube size on the flow rate within the pump, two tubes were fitted inside the pump in succession. The first tube had a larger inner radius of 3 mm, while the second tube had an inner radius of 2 mm.

To measure the effect of the rotation speed of the pump on the flow rate, the speed of the DC Motor was varied from 0% to 100% of the maximum voltage in steps of 12.5% by providing the appropriate PWM signals through the Arduino connected to the Motor Driver.

In addition to investigating the flow characteristics of the pump, the intermittent performance of the pump is also studied. Infusion pumps are programmable devices that allow the delivery of precise amounts of fluid directly inside the subject. These devices have a wide variety of applications in the medical field. Since they permit the infusion of fluids in a specific target location, infusion pumps technology shows higher efficiency and smaller side effects compared to other dosing strategies.

The application of the small scale rotary peristaltic pump as such an infusion device is studied. The pump is controlled in order to precisely control its angular rotation and thus perform intermittent injections.

The efficacy of peristaltic pumps is greatly affected by the extent of the compression of the tubing system between the rotor and the stator. A high compression leads to a reduced tube lifetime, while a low compression can cause high amounts of slip back or leakage flow. Therefore, an optimum level of tube compression must be aimed for. 'Occlusion' is the term used to define the minimum gap in the pump tubing based upon the flexibility of the tube. The occlusion is typically 10% to 20%. The value is lower for harder tubes and higher for softer ones. If optimal occlusion is achieved, both the shear stress upon the tubing as well as the back flow or leakage are reduced.

Peristaltic pumps possess the ability to function in two different methodologies, either continuously or their rotations can be controlled to be restricted so as to deliver select amounts of fluid in an intermittent, or non-continuous, mode. When such a partial revolution is executed within the pump, the amount of fluid contained between two adjacent rollers determines the net flow ejected.

The Arduino wired to the Motor Driver helps to exact precise control over the pump angular rotations and thus emulate the performance of the peristaltic pump in the intermittent mode. The Arduino program allowed for providing different delays between consecutive releases.

# Chapter 6

# Results and Discussion

Experiments were carried out for both pump tube sizes by adjusting the operating settings and measuring the fluid amount (water at room temperature) transported between two reservoirs. The pump and the reservoir were kept at the same geodetic height so that any external pressure gradients would not affect the flow.

The observation tables of both results of the flow characteristics measurements for each tube size have been displayed.

| Percentage Duty Cycle | PWM argument | Time (s) | Flow Rate (cm3/sec/100) |
|---|---|---|---|
| 0 | 0 | NA | 0 |
| 12.5 | 32 | NA | 0 |
| 25 | 64 | NA | 0 |
| 37.5 | 96 | 6 min | 22.81 |
| 50 | 127 | 2 min 49.82 sec | 48.29 |
| 62.5 | 159 | 2 min 09.39 sec | 63.45 |
| 75 | 191 | 1 min 44.63 sec | 78.46 |
| 87.5 | 223 | 1 min 34.46 sec | 86.92 |
| 100 | 255 | 1 min 24.44 sec | 97.23 |

*Table 1. Observation Table for the Result of Flow Characteristics Measurements for Tube of Inner Radius 3 mm.*

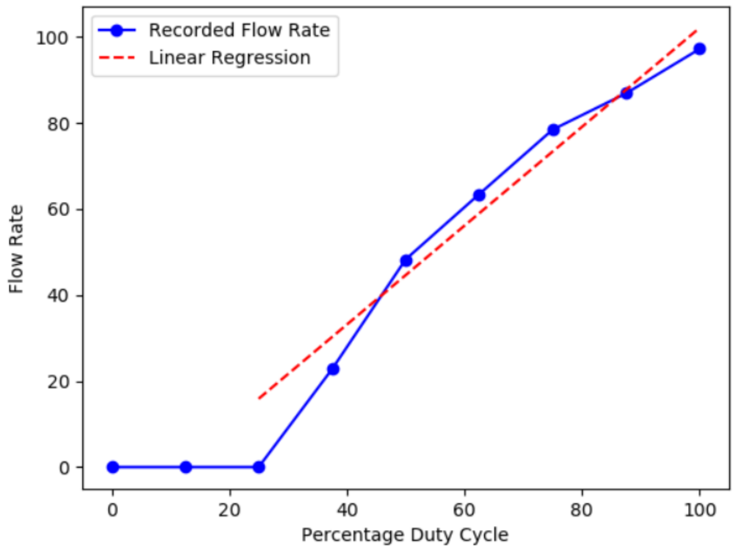

*Figure 7. For Inner Radius 3 mm, the Flow Rate is Plotted against the Percentage Duty Cycle of the Pump. The linear regression of values above 35% Duty Cycle are also plotted.*

| Percentage Duty Cycle | PWM argument | Time (s) | Flow Rate (cm3/sec/100) |
|---|---|---|---|
| 0 | 0 | NA | 0 |
| 12.5 | 32 | NA | 0 |
| 25 | 64 | NA | 0 |
| 37.5 | 96 | 11 min 32.43 sec | 11.86 |
| 50 | 127 | 6 min 49.23 sec | 20.06 |
| 62.5 | 159 | 4 min 33 sec | 30.07 |
| 75 | 191 | 3 min 46.28 sec | 36.28 |
| 87.5 | 223 | 3 min 24.91 sec | 40.07 |
| 100 | 255 | 3 min 04.92 sec | 44.4 |

*Table 2. Observation Table for the Result of Flow Characteristics Measurements for Tube of Inner Radius 2 mm.*

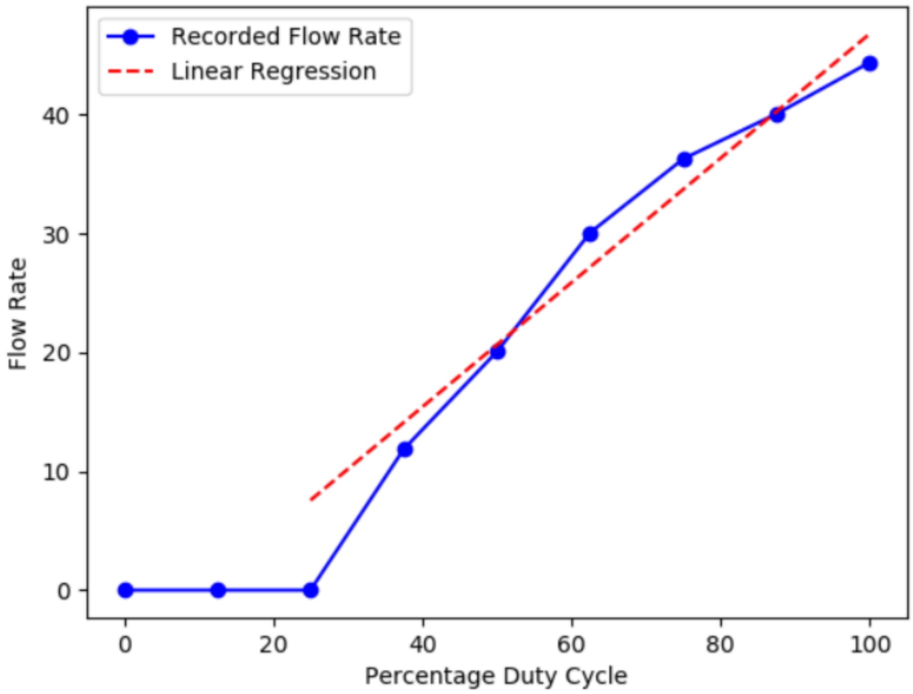


*Figure 8. For Inner Radius 3 mm, the Flow Rate is Plotted against the Percentage Duty Cycle of the Pump. The linear regression of values above 35% Duty Cycle are also plotted.*

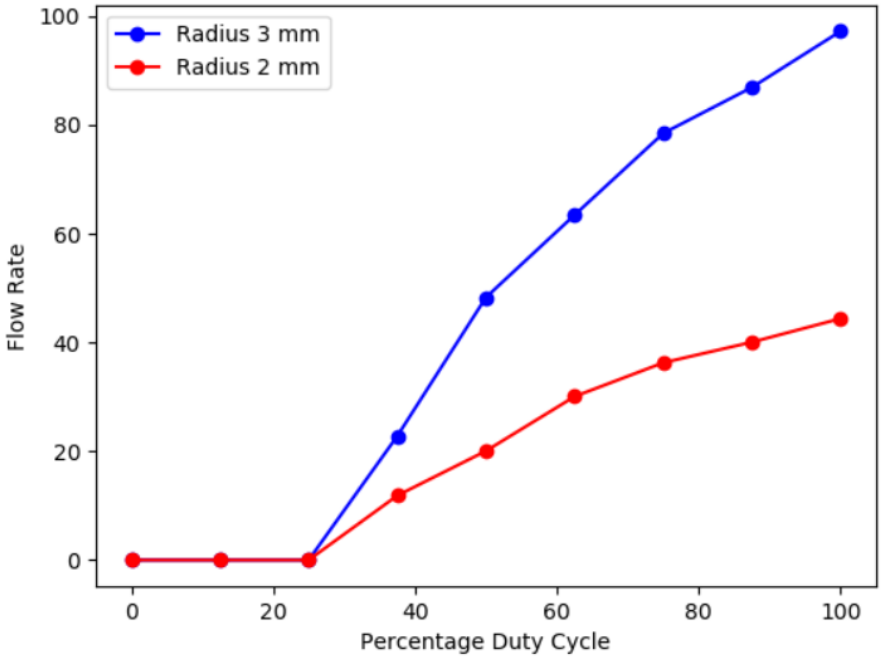


*Figure 9. Comparison of the plots between the Flow Rate and the Percentage Duty Cycle of both tube sizes*

It can be seen that in overall performance, the volume flow rate of the peristaltic pump increases as the speed of the rotor increases. As expected from the theoretical analysis, the volume flow rate increases linearly with the rotor speed of the peristaltic pump. As can be seen from the observation table, the results are in close alignment with the results of the linear-regression analysis which have been plotted in the same graph.

For fixed values of the tubing size and the rotor speed, the peristaltic pump outputs a stable flow rate, leading to the pumped fluid volume increasing linearly with time. In addition, it was observed that the pump motor would either lag or refuse to work at all below voltage duty cycles of around 35%. This is because at levels of power this low, the pump fails to overcome the frictional constraints arising from manufacturing and design tolerances inherent to the pump, which restrict the practical rotational speed.

Because of the above mentioned reasons, the calculation of the linear regression curve was done with the results of duty cycle values ranging from 35% to 100%.

Comparing the flow rates between the two tube sizes, it was observed that the flow rate was higher for the tube with the larger inner diameter. It is reasoned that, since both the inner and outer diameter of one tube are proportionately larger than the other, the occlusion ratio remains the same and an equivalent back flow exists in both tubes, and thus the tube with the larger inner diameter gives a proportionately higher flow rate.

Finally, to test the intermittent flow functionality of the pump, the motor was made to rotate at precise angles using the Arduino program, and various delays were provided between consecutive releases. This was done to characterize the pump in an intermittent operation mode, such that it could be applied in practical situations such as on-demand drug delivery operations that need non-continuous release, wherein a precise fluid release is succeeded by a required pause in the flow.

Five intermittent release conditions were programmed into the pump, and the impact of each of these lag times on the output precision was observed and evaluated. The lag times were as follows: continuous rotation (0 lag), 5 seconds, 10 seconds, 20 seconds and 30 seconds of pause time between every intermittent release. This pause time was affected every 90 degrees of rotation of the motor.

It was observed that the presence of lag times between releases led to a greater output precision. In addition, speed variation of the motor did not have much of an effect on the output flow. As expected, it was seen that the output variance increased when the pump was operated without any lag times, that is, in continuous mode. Increasing lag times in the intermittent led to a general increase in the output precision, although it was seen that the longer lag times led to cumulative volume decrease in the output reservoir due to evaporation.

## Chapter 7

# Conclusion

This report presents a study of peristaltic pumps in the following fields: A study of their literature, in both practical applications and theoretical analyses, a study of their design and construction in order to select an appropriate pump for experimental work, and finally an experimental analysis of the flow characteristics of a rotary peristaltic pump.
The literature review was thorough and was conducted on a wide array of research topics. These included the basic principle of peristalsis, the types of peristaltic pumps available, their construction, working and benefits, as well as giving an overview of the current state of research in this field and the various fronts which promise innovation in pump design.

The objective of this section was to study and summarize the most important properties of these pumps. Disadvantages of peristaltic pumps were also explored such as the requirement of calibration or control when new tube segments are inserted into the pump, the pulsatile nature of the flow, the dependence on the pressure gradient being applied at the ends of the pump and the need for compensation for the inaccuracies present in the pump innate to the production methods.

A review of the literature concerning the fluid flow analytics of peristaltic pumps was also conducted. This report went over the nature of flow within peristaltic pumps, the mathematical reasoning behind peristalsis and the various parameters which affect the nature of the flow.

A pump of appropriate type was successfully chosen to perform the desired experimental analysis. A rotary pump with 3 rollers with easy assembly and disassembly was deemed to have the necessary properties required for our purposes. The construction and working of the pump were discussed in detail.

Finally, an experimental study was performed on the pump to understand its flow characteristics. The flow rate of the pump was tested against two structural parameters of the pump, and the results of these tests were compared to and confirmed the literature on the analytical theory behind these fluid flow profiles. In addition, structural flaws in the pump were recognized which were responsible for rendering the pump non-functional at low flow rates.

Finally, the reliability and precision of the pump in an ‘intermittent mode’ was tested. The small size rotary pump was successfully operated in non-continuous mode, and a reprogrammable capability was provided to vary the delay between continuous ejections based on the required dosing precision.

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