Design and Fabrication of a Pump for Peristaltic Flow of variable viscosity fluids

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ABSTRACT

Due to the widespread use of peristaltic pumps in the pharmaceutical industries, manufacturers are searching for new type of pumping machines, based on the mathematical models. Researchers have predicted the results of peristaltic transport in many applications mathematically and failed to interpret the results. One of the reasons is the difficulties faced in generation of peristaltic transportation of the fluid mechanically. This paper has made an effort to generate the design & characteristics of peristaltic transport of the fluid. The parameters identified in designing the pump are generation of constant contraction and expansion of the tube with small amplitudes, considerable pressure development in the fluid and flow characteristics. The fabricated model is different from existing conventional pumps while the characteristics of the pump being same.

Keywords : Peristaltic pumps, Newtonian, Non-Newtonian fluids

Introduction

1.PERISTALSIS

One of the biological features of smooth muscles of the human system is the power of rhythmic contraction. These rhythmic contractions are essential for transportation of physiological fluids, for passage of food through the esophagus, for movement of chime through the small intestine, the colonic transport in the large intestine, the passage of urine from the kidneys to the urinary bladder through urethra, spermatic flow in ducts of the male reproductive track, the movement of ovum in the fallopian tube of the female reproductive system and the circulation of blood through small blood vessels.

These contractions may be of high, medium or low degree and are associated with negligible expenditure of energy. The tonic mechanism is relatively insusceptible to fatigue and heat production. Some physical, electrical and chemical reactions are responsible for this phenomenon. These movements occur as a natural mean of pumping biological fluids, passage of food and other transportation of biological products in the body by continuous periodic muscular oscillations called peristalsis. A true peristalsis is a coordinated reaction in which a wave of contraction is preceded by a wave of relaxation.

The basic principle of peristalsis helped in designing the roller pumps, which are useful in pumping fluids without being contaminated due to contact with pumping machinery. The biomechanical pumps fabricated to save blood and other fluids from any possible contamination arriving out of the contact with the pump machinery while pumping the fluid is an excellent example for this phenomenon.

The peristaltic motion found in physiological flows is classified into different categories, a few of them being (1) Rush peristalsis (2) Anti –peristalsis and (3) mass peristalsis.

2.PHENOMENA ASSOCIATED WITH PERISTALSIS:

Two important phenomena in peristalsis are (i) Reflux and (ii) Trapping.

Reflux: There are two contradicting definitions of Reflux in peristaltic motion. Shapiro and his associates propagated the first one while the second one was by Fung and his colleagues. (Shapiro A.M. 1967, pumping and retrograde diffusion in peristaltic waves. Proc. Workshop is urethral Reflux in children 109-126) (Fung Y.C. and Yen C.S. 1968, Peristaltic transport Trans ASME.E.J.Appl.Mech.35 669-675). Shapiro gave his definition with the back word migration of bacteria from the bladder to the kidneys. According to him, it refers to the presence of fluid particles that move on an average, in the direction of oppisite to the net flow near the walls. The backward migration takes place near the walls. It was experimentally verified by Weinberg et al., (1971) (Weinberg, S.L., Eckstein, E.C. and Shapiro A.H.) (1971) –An experimental study of peristaltic pumping.J.Fluid Mech., 461-479). According to Fung, it is the average mean flow reversal near the axis of the duct. Shapiro proposed that Eulerian time mean velocity must be taken into consideration whereas Fung considered Lagrangian displacement of fluid particles.

3.TRAPPING

Shapiro et al. (1969) (Shapiro A.H.,Jaffarin, M.Y. and Weinberg S.L.(1969) theoretically discovered it. Peristaltic pumping with long wave lengths at low Reynolds number. (J.Fluid Mech.37, 799-825) that at high flow rates and large occlusions, there is region of closed stream lines in the wave frame and thus some fluid is found trapped within a wave of propagation. The trapped fluid mass is found to move with the mean speed equal to that of the wave.

In the design of pumps, the inner surface of the tube with permeable wall is considered and presented mathematically. It is assumed that the plug flow is at an inclination of $\acute{\alpha}$ and wave generated on the surface of the tube by contraction and expansion of the tube. From the analysis, parameters evaluated are dimensionless pressure, discharge and friction. The fluid considered for the plug flow as a Newtonian fluid.

Based on the mathematical analysis many researchers attempted and designed many models.

4. BACKGROUND DESIGN OF PERISTALTIC PUMP

A variety of micron- and millimeter-scale fluid device designs such as chemical analysis and drug delivery systems require miniature fluid pumps. Miniature pumps have been widely studied and are reviewed in [19, 5] together with associated applications. For many applications, an ideal miniature pump would supply sufficient flow rate and pressure, while having a low voltage requirement, low power consumption, a simple control system, and low cost. Presented here, a miniature peristaltic pump which is potentially competitive with respect to most or all of these criteria. Peristaltic pumps move fluid by exerting forces on the outside of a pumping chamber [5], which often consists of a flexible tube containing the fluid. Many peristaltic pumps have the advantage that the pump actuator components do not touch the fluid and that the pumping chamber can be made disposable [71] to ensure sterility and prevent cross-contamination. Macro peristaltic pumps have been micro fabricated using polydimethylsiloxane (PDMS) [110], PDMS bonded to glass [77, 35], or glass bonded to silicon [48, 18]. A series of two or more actuators compress regions of a channel (the pumping chamber) to produce a peristaltic wave. In other macro peristaltic designs, the pump chamber is created from a section of flexible tubing and the pumping action is created by motor-driven rollers [9], magnetic balls [52], or drops of magnetic liquid which compress the tube. Described a novel macro peristaltic pump which uses a single reciprocating actuator motion to produce pumping. This pump uses off-the-shelf tubing and can be manufactured using conventional materials and methods including injection molding, stereo lithography, or CNC machining. Presented in detail a version of the pump where the required linear actuation motion is achieved using a small commercial motor and a chain drive. The motor actuated pump achieves high flow rates (0.8 ml/min) and can operate under relatively high back pressures of up to 48 kPa. The latter values are on par with or higher than many miniature pump devices [19, 5]. The pump is self-priming, tolerant of bubbles and particles, and can pump liquids, gases, foams, and gels. The pump consumes 90 mW of electrical power at 220V, and 7 amps allows control of flow rate by controlling voltage. Only one size of the pump, and created smaller and larger versions which achieve 0.1× to 5× the nominal flow rate and/or higher back pressures (up to 69 kPa).

5. TUBE PUMPS

Lower pressure peristaltic pumps typically have dry casings and use rollers along with non-reinforced, extruded tubing. This class of pump is sometimes called a "tube pump" or "tubing pump". These pumps employ rollers to squeeze the tube. These pumps have a minimum of 2 rollers 180 degrees apart, and may have as many as 8, or even 12 rollers. Increasing the number of rollers, increase the pressure pulse frequency of the pumped fluid at the outlet, thereby decreasing the amplitude of pulsing. The downside, by increasing number of rollers, it proportionately increases number of squeezes, or occlusions, on the tubing for a given cumulative flow through that tube, thereby reducing the tubing life.
There are two kinds of roller design in peristaltic pumps:

5.1.FIXED OCCLUSION - The rollers have a fixed locus as it turns, keeping the occlusion constant as it squeezes the tube. This is a simple, yet effective design. The only downside to this design is that the occlusion as a percent on the tube varies with the variation of the tube wall thickness. Therefore, a section of tube with greater wall thickness, but within the accepted tolerance, will have higher percent occlusion, which increases the wear on the tubing, thereby decreasing the tube life. Tube wall thickness tolerances today are generally kept tight enough that this issue is not of much practical concern. For those mechanically inclined, this may be a constant strain operation.

5.2. SPRING-LOADED ROLLERS - As the name indicates, the rollers are mounted on a spring. This design is a bit more elaborate than the fixed occlusion, but helps overcome the variations in the tube wall thickness over a broader range. Irrespective of the variations, the roller imparts the same amount of stress on the tubing that is proportional to the spring constant, making this a constant stress operation. The spring is selected to overcome not only the hoop strength of the tubing, but also the pressure of the pumped fluid. The operating pressure of these pumps is determined by the tubing, and the motor's ability to overcome the hoop strength of the tubing and the pressure.

DESCRIPTION OF PUMP

Based on the present literature, it is found that most of designs lack in contributing the mathematical models and most of the designs were presented on two parameters plug pressure and flow rate in the design of the pumps and presented the existing of peristaltic effect. This section describes the pump design and its operation with experiments conducted.

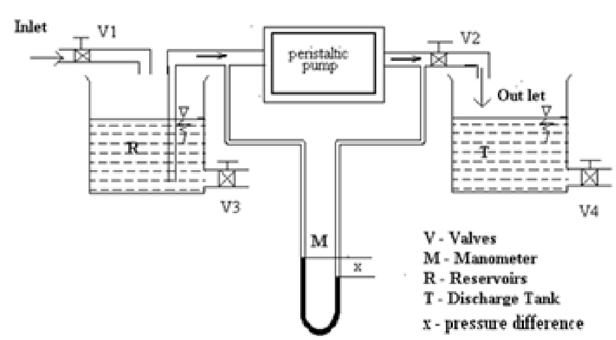

Fig: 1. Schematic arrangement of experimental set up of the peristaltic pump

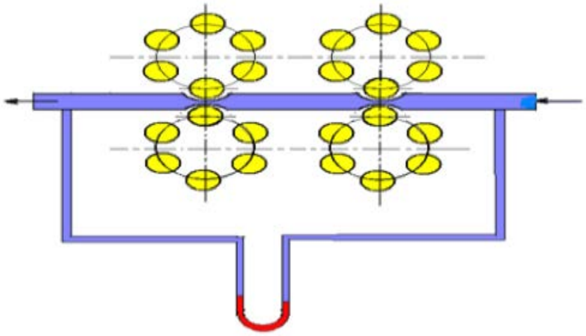

FIG : 2. The schematic arrangement of pump with rollers

MOTOR-DRIVEN PUMP DESIGN AND OPERATION PRINCIPLE

Based on the presented literature, the author has attempted to design based on mathematical model. The pump consists of chain drive mechanism, roller cams flexible hose. The principle involved in this mechanism is the roller cams are passed over the silicon hose on upper and lower surface at two sections. Therefore, the cams are so arranged that the four rollers in a direction, such that the linear peristaltic flow exists. The presence of two pairs of roller cams at two sections to operate as a value added mechanism. The schematic of setup in which the pump draws liquid from the inflow reservoir as the flow enters at section-I (i.e first pair of cam rollers) the hose compresses and expands, the flow between the first section and the second section of roller causes the raise in pressure and releases the flow as the second set of rollers are in action, this process continues as soon as the initial required suction pressure between inlet and outlet is maintained. Once the suction pressure develops, the flow will be continuous with the peristaltic effect. The next section, describes elaborately the design and development of the peristaltic pump.

REQUISITE CHARACTERISTICS FOR DESIGNED PUMP

The peristaltic effect consists of the flowing fluid expands and contracts in the tube and evoluation of change in pressure and discharge are computed mathematically. Hence, an attempt is made to bring the design aspect which consists of symmetrical wave characteristics. In the present work the design is made by locating the cam rollers on both upper and lower surfaces of the tube as shown in the figure below.

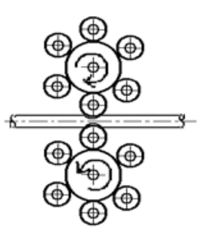

Fig: 3. Mechanism of peristalsis

The second requisite properties to be satisfied are wave length of the fluid flow which is assumed as a sinusoidal wave and constant in the present case of designed prototype model. And also two consecutive pairs of cam rollers are placed as shown in the figure below to achieve continuous wave form. Another application of two consecutive pairs of roller cams in which they can act as an actuator valve mechanism which helps in generating the suction pressure.

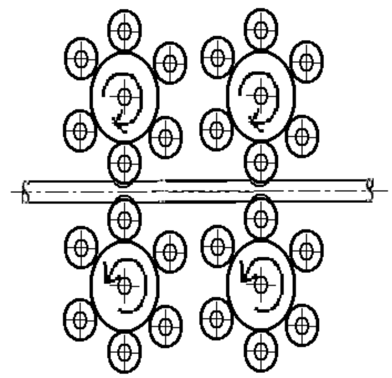

Fig: 4. Cam roller arrangements in peristaltic pump

FACTORS INFLUENCING THE FLOW RATE

The factors influencing the flow rate are

1. Type of fluid – Newtonian and Non – Newtonian
2. Viscosity
3. Chain speed
4. Suction pressure
5. Rescue height

The applications of these types of pumps are widely used in Bio-medical, food processing industries where the fluid is not directly in contact with casing of the pump. These applications in industry have certain influence in the above said features. Hence, the design of the peristaltic pump made with certain pre assumed conditions. Initially, the pump characteristics are evaluated with Newtonian and then with non-Newtonian fluids, which then depends on the viscosity of the fluid and of course the development initial suction pressure which cause the fluid to flow. The pre-assumed characteristics of the pump are as follows.

CHARACTERISTICS OF PERISTALTIC PUMP

The important characteristics of peristaltic hose pumps are listed below:

- Characterized as a low pressure pump with cam roller mechanism flows in axial direction.
- Operating capacity can go up to 0.003 N/m2.
- The flexible hose is what holds the fluid for the purpose of transmission through the pump.
- Rotor is associated with certain rollers that enable the inner hose go in circular motion and flow is in axial direction.

Schematic of setup to quantify pump pressure, flow rate, and power performance. The pump draws liquid from one of two identical upstream liquid reservoirs 1 and 2. Arrows indicate flow direction. The flow rate can be found from the outlet tank.

Let the differential manometer contains a liquid which is

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heavier than the liquid flowing through the pipe.

Sh = specific gravity of heavier liquid
So = specific gravity of the liquid flowing through pipe
X = difference of the heavier liquid column in U-tube
Then, h = x [(Sh/ So)-1]

DESCRIPTION OF THE PUMP AND OPERATION:

The design of macro peristaltic pump of self priming characteristics with linear actuator is designed. The pump consists of motor (0.062kW) driven by sprocket and chain drive mechanism each sprocket is fixed to a circular plate consisting of six rollers of 20mm diameter as shown in the figure .As the motor drives the chain drive the arrangement is made such that the rollers will pass on to the surface of the silicon tube in single direction that is the four sprockets with rollers top and at the bottom will rotate in opposite direction such that the flow in the tube always in single direction. The rollers compress and release the silicon tube and will act as a valve at two junctions which creates a negative pressure - pulse causing the fluid flow in the tube and generates peristalsis characteristics of the fluid.

TABLE: 1. DESIGN OF CHAIN DRIVE

Design of Chain Drive							
		Motor		CAM			
				CAM-1	CAM-2	CAM-3	CAM-4
No. design of Sprockets	N	18		28	28	28	28
Diameter	D	35. 5		55	55	55	55
Pitch	P	6.2		6.2	6.2	6.2	6.2
Perimeter		111.527		172.79	172.79	172.79	172.79
Length of the chain	L	721	Mm				
Speed of the pinion		100	Rpm	64.10256	64.10256	64.10256	64.10256
Speed of the pinion		1.67	Rps	1.068376	1.068376	1.068376	1.068376
V_{max}		186.95	m/s	185.8598	185.8598	185.8598	185.8598
V_{min}		184 .11	m/s	184.6912	184.6912	184.6912	184.6912
Polygon effect		0.01527		0.006301	0.006301	0.006301	0.006301

MOTOR DRIVEN PUMP AND OPERATION:

The pump shown in the figure consists of four important parts

1. Silicon tube
2. Roller cams
3. Motor
4. Sprocket and chain drive mechanism

To describe its operation to divide these into four functional components

1. Flexible tube
2. Roller cam mechanism
3. Valve operation
4. Chain and sprocket mechanism

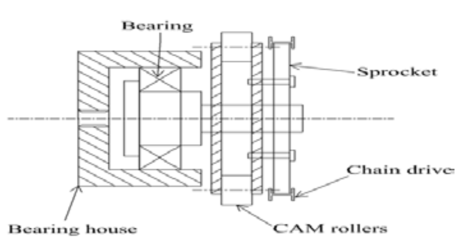

Fig: 5. Cross sectional view of bearing hose, cam rollers and sprocket mechanism

The motor connected to this mechanism has the following specifications. The motor shaft is fixed to 20mm sprocket for driving the four cam wheels. Each cam wheel consisting of six roller cams. This particular cam is fixed to a bearing house as shown in the Fig:7. The design of the roller cams chain and sprocket mechanism is as follows.

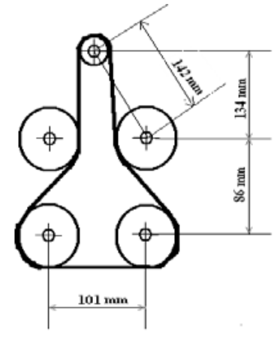

Fig: 6. Chain drive mechanism

SPECIFICATIONS OF THE FABRICATED PUMP

1) Occlusion

The minimum gap between the roller and the housing determines the maximum squeeze applied on the tubing. The amount of squeeze applied to the tubing affects pumping performance and the tube life - more squeezing decreases the tubing life dramatically, while less squeezing can cause the pumped medium to slip back, especially in high pressure pumping, and decreases the efficiency of the pump dramatically and the high velocity of the slip back typically causes premature failure of the hose. Therefore, this amount of squeeze becomes an important design parameter. The term "occlusion" is used to measure the amount of squeeze. It is either expressed as a percentage of twice the wall thickness, or as an absolute amount of the wall that is squeezed.

Let y = occlusion

g = minimum gap between the roller and the housing.

t = wall thickness of the tubing . Then,

y = 2t - g (when expressed as the absolute amount of squeeze)

y = (2t-g)/(2t) × 100 . (

(when expressed as a percentage of twice the wall thickness)

The occlusion is typically 10 to 20%, with a higher occlusion for a softer tube material and a lower occlusion for a harder tube material. Thus for a given pump; the most critical tubing dimension becomes the wall thickness. An interesting point here is that the inside diameter of the tubing is not an important design parameter for the suitability of the tubing for the pump. Therefore, it is common for more than one ID be used with a pump, as long as the wall thickness remains the same.

2) Inside diameter

For a given rpm of the pump, a tube with larger inside diameter (ID) will give higher flow rate than one with a smaller inside diameter. Intuitively the flow rate is a function of the cross section area of the tube bore.

3) Flow rate

Flow rate is an important customer requirement. The flow rate in a peristaltic pump is determined by many factors, such as:

1. Tube ID - higher flow rate with larger ID
2. Length of tube in the pump measured from initial pinch point near the inlet to the final release point near the outlet - higher flow rate with longer length
3.Roller RPM - higher flow rate with higher RPM

Interestingly enough, increasing the number of rollers doesn't increase the flow rate; instead it may decrease the flow rate somewhat by reducing the volume of fluid between the initial pinch point and the final release point. Increasing rollers does tend to decrease the amplitude of the fluid pulsing at the outlet by increasing the frequency of the pulsed flow. The experimental setup is shown in Fig: 7.

METHODOLOGY

The fluid is contained within a flexible tube fitted inside a circular pump casing (though linear peristaltic pumps have been made). A rotor with a number of 'rollers', 'shoes', or 'wipers' attached to the external circumference compresses the flexible tube. As the rotor turns, the part of tube under compression closes (or occludes) thus forcing the fluid to be pumped to move through the tube. Additionally, as the tube opens to its natural state after the passing of the cam (restitution) fluid flow is induced to the pump. This process is called peristalsis. The establishment of peristalsis flow by a pump is the main aim of the many researchers. Some of the models existing are discussed in the literature review. Hence, the Author has made an attempt to model, design and fabricate the new type of pump than the existing one.

Fig: 7. The experimental setup in the inset chain and roller mechanism

CONCLUSIONS

The literature review shows that reviewers / authors were researched in depth mathematically and thousands of mathematical models considered Newtonian and non Newtonian fluids. But, most of the researchers have not shown the flow characteristics in the physical models interpreting the mathematical models. In the present research work, peristaltic transport with single fluid and fluids with two different viscosities was presented. Considering the parameter ∅ = 0.6 and wavelength , the peristaltic pump were designed, which is a new type of pump with cam rollers. The design aspects are presented. Based on the Results and Discussion the following conclusions are drawn followed by scope for the future work.

1.The mathematical model, considered for Non Newtonian fluid flow under peristalsis is presented. The various parameters considered are varying ∅, λ, n and the evaluated pumping characteristics, are non dimensional pressure and discharge.

2. In the present study and design analysis ∅ is limited to 0.6, λ is 0 mm and n=1(Newtonian fluids) are considered for the design of peristaltic pump.

3.In the present study of two fluids of different viscosity flowing in plug flow with Newtonian (n=1) and non-Newtonian (n>1 i.e. 3) are considered and the effect of peristalsis is presented.

4. The operating conditions considered in the design aspect are:

i) Speed should be constant and limited to 100 rpm.

ii) The wavelength of the peristaltic wave depends on the cam rollers.

iii) During design, it is considered that the silicon hose for the designing purpose is 16mm diameter for which the calculated ∅ is 0.6 which is maintained during pumping.

5. The pressure level achieved in the experimentation is

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very small, since wear between the rollers and the silicon hose is more and the corresponding discharge values are recorded for which the variation is negligible due to very small rise in pressure.
6. The corresponding design variables considered are verified with the theoretical work which shows almost co-incidence.

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