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Miniaturized Flexible Flow Pump using SMA Actuator

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Abstract

Fluid pumps are one of the major components in engineering domain. The presence of fluid pumps in the medical field has gained momentum and has become an essential factor considering handling of life saving drugs and fluidic transport within the body. The need for a miniaturized flow pump based on size, application and capacity has driven the evolution from robust size pumps to MEMS based pumps. This paper proposes a novel methodology of actuation based on flow generation in a flexible tube by inducing variable pressure difference within the tube by external actuation by Shape Memory Alloy (SMA) wires. The proposed method helps in achieving miniaturization and bidirectional flow of fluid which is not possible in traditional pumps. These miniature pumps find their application where there is need for contactless operation between the working fluid and the pump, to avoid contamination of the working fluid or when the working fluid is aggressive or toxic. A detailed insight of the working principle and the conceptual design is provided. Preliminary test results and analytical results are presented.

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Keywords: Micro pumps; shape memory alloy actuators; peristalsis; miniature pump;bio-compatible pump;flow across variable cross section;smart devices

Nomenclature

T	Present Temperature (°C) of SMA
m	Mass (kg)
c_p	Specific Heat (J/kg °C)
i	Current (A)
T	Temperature (°C)
t	Time (s)
R	Resistance of SMA Wire (Ω/m)
h	Heat transfer Coefficient(W/m^2)
A	Area of SMA Wire(m^2)
T_a	Ambient Temperature (°C)
T_o	Reference Temperature (°C)
α	Coefficient of Thermal Expansion (1/°C)
ρ	Density of silicone rubber tube (kg/m^3)
μ	Dynamic Viscosity (kg/ms)
P	Pressure (Pa)
u	Velocity (m/s) of fluid
$\dot{V}_{in}$	Volumetric flow rate of fluid at inlet (m^3/s)
$\dot{V}_{out}$	Volumetric flow rate of fluid at outlet (m^3/s)
n	Unit normal of Boundary

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1. Introduction

A variety of micro and milli-scale fluidic device for chemical and drug delivery systems require miniature fluid pumps. These pumps have been widely studied and are reviewed in [1] together with associated applications.[1]From biology and medicine to space exploration and microelectronics cooling, coolant movement though micro heat exchangers [2, 3] on the order of a milli level are increasing exponentially. The capillary principle which is widely used in many current systems requires fluid to be pumped and controlled using micro pumps. For example, biological samples must be moved through the components of miniature assay systems [4]. Micro-fluidic transport requirements such as these can sometimes be met by taking advantage of passive mechanisms, most notably surface tension. The peristaltic effect found in the body's muscular system for movement of contents through the digestive tract using radial contraction of the muscle tube offers a good alternative over traditional micro pump in terms of operation and compatibility. The use of bio mimetic peristaltic principle in designing a self priming roller free miniature peristaltic pump with single reciprocating actuator, which can be actuated manually and using SMA has been discussed by Shkolnikova et al[5] .

Further developments have led to the concept of usage of SMA in the peristaltic effect for noiseless operation and bio compatible operation. The Shape memory effect in SMA occurs due to temperature and stress dependent transfomation in the material's crystalline structure between two different phases called martensite and austenite. Martensite, the low temperature phase is relatively soft compared to the austenite phase which is a high temperature phase and is relatively hard. If a material is allowed to cool from a higher temperature state, the austenite state is converted into martensite state. The intermediate twinned martensite state is of uniform crystal dislocation such that all lattice points in the crystal are disordered in a unique manner. The final state is the martensite state which is the deformed state. The special property that allows shape-memory alloys to revert to their original shape after heating is that their crystal transformation is fully reversible. During the reversing process if the SMA wires are constrained, it exerts large force opposing the constraining force while returning to the austenite phase. This behaviour had led to the actuation principle of SMA material. SMA actuators have been an ideal choice in robots for their control [6,7,8], valves, pumps and aerospace applications due to their distinguishable properties such as high power–to-weight Ratio, high possibility of miniaturisation and low power consumption [7] . A special process called as training is required to derive maximum benefits from such kind of smart materials which are discussed by Sreekumar et al [9]
For many applications, an ideal miniature pump would supply sufficient flow rate and pressure, while having low power consumption and a simplified design. The paper aims at developing such a pump which is potentially competitive with respect to both the criteria using shape memory alloys.

2. Methodology

Most micro-pumps are based on either of the two principles: Displacement pump or Dynamic pump. Displacement pumps are reciprocating micro-pumps that use oscillatory or rotational movement of mechanical parts to displace fluids. Dynamic pumps add energy continuously to the working fluid in terms of momentum or pressure [1].The setup of the device is achieved by mimicking arteries or veins of human body which transport fluid by varying their cross-section and thereby causing continuous circulation of fluid. Hence the current setup falls under the dynamic pump category. The artery is mimicked by a flexible tube coupled with a series of SMA wires wound around the flexible tube. The SMA actuation results in contraction of the flexible tube which consequently leads to variation in cross section of the tubes creating a pressure difference effect [10].

The SMA wire is actuated in a definite cycle for fluid flow in a unidirectional way. The necessary heat for SMA actuation is provided from external source and constant switching of ON/Off of power supply resulting in heating and cooling of the SMA material. The fluid is pumped through the tube where fluid moves due to the actuation of SMA material and due to the fluid displaced in the tube by actuation, fluid flows in to fill the space left by the displaced fluid. The number of SMA actuation units is selected based on the head of fluid to be pumped and the number of SMA coil turns is selected based on the wall thickness of the tube in which the fluid flow occurs.

The layout depicted in Figure 1 (a) was proposed by Prashanth et al [10] whose practical working can be implemented feasibly by connecting the SMA wire to a structure. The revised schematic layout is proposed in Figure 1(b).The structural material provides rigidity to the entire wire assembly holding it in place. The base structure though adds to the weight of the actuation mechanism it is an important unit for good fastening of the SMA wire and to provide easy heating through power source where lead terminals are connected to nut bolts provided within the structure to which the SMA wire are fastened.

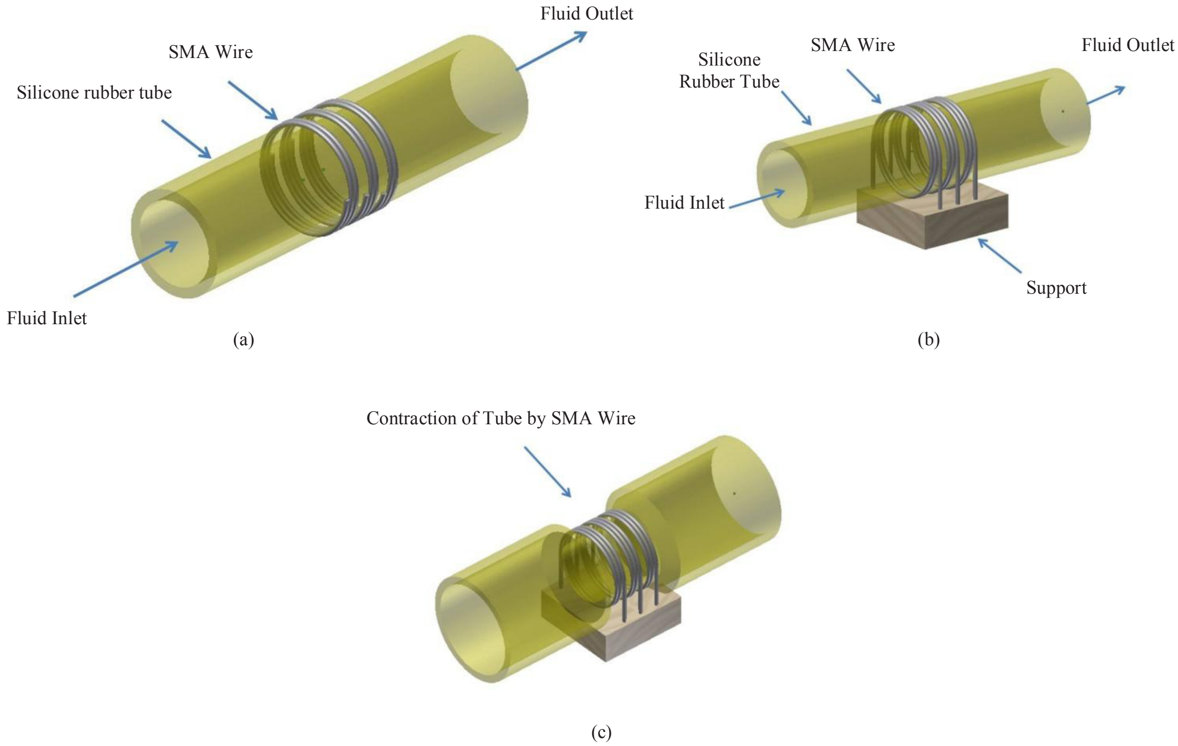


Figure 1 (a) Initially conceived Schematic Layout; (b) Modified Layout; (c) Actuated SMA wire over flexible tube

The actuation of the flexible tube by the SMA wire is depicted in Figure 1 (c). The figure depicts a simultaneous actuation of three sets of SMA wire for combined actuation force and timing of actuation which aids to propel the fluid forward. The tube opted for the application is silicone rubber tube as they are one of the ideal flow tubes in the regard of peristaltic pumps due to their flexible nature. The silicone rubber tube also offers a great advantage in the temperature withstanding capacity where they are capable of withstanding temperatures until 600°C. This property of silicone rubber persists any deformation of its structure and change in properties in the current application where the SMA wires are directly wound on to the silicone rubber tube which is heated by current flow, this process results in a temperature gradient along a very small width of the tube where SMA wires are wounded which results in high temperature concentration at a particular width which would melt normal tubes, hence silicone rubber proved to be an ideal choice.

The SMA wire used in the application is a flexinol wire which is a muscle wire. Muscle Wire is an extremely thin wire made from Nitinol (a nickel-titanium alloy) that is known for its ability to contract when heat input is applied. The possibility of contraction of flexible tube is possible only using a muscle wire unlike untreated shape memory alloy which only regains its original form upon heating whereas visible contraction is the desired effect, which can be obtained only through treated muscle wire.

3. Experiment

The SMA wire is wounded as a coil around the silicone rubber flexible tube as shown in the figure 2. This mechanism despite the lower actuation force provided has a greater advantage in compactness and least complexity structure. A structure exists for the sole purpose of mounting the SMA wire on the flexible tube and constraining the wire from any misalignment. The base structure also serves as the point of contact with the power supply. The SMA wire directly contact the flexible tube in this mechanism hence compelling the use of high temperature withstanding flexible tube as heat concentration increases along the contact area.

(a) (b)

Figure 2 (a) Miniature Flexible SMA Wire Clamping; (b) Size representation of SMA Wire Clamp

The silicone rubber tube of inner diameter 4mm and outer diameter 5mm is taken for experimentation. Different patterns of coil arrangement have been carried out to investigate the SMA wire behaviour during actuation on the tube.

3.1 Experimentation Layout

The experimental setup is depicted as in figure 4

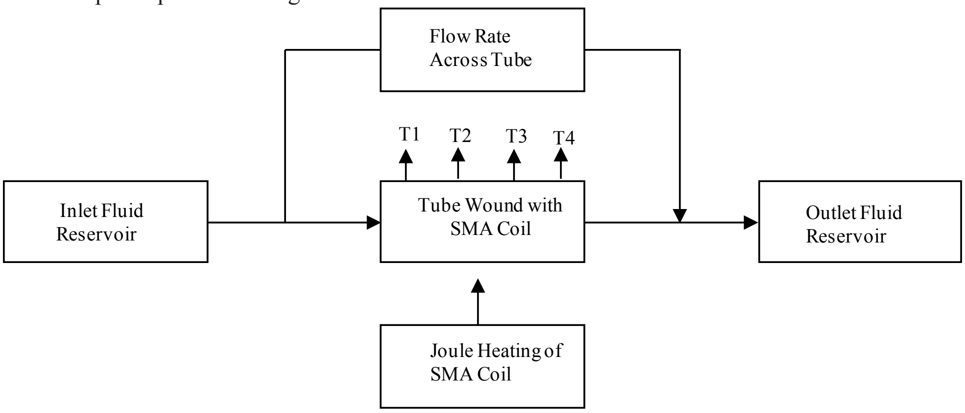


Figure 3 Experimental Layout

3.2 Materials Considered

Tube: Silicone rubber tube is considered as the flexible tube material

SMA Coil: The SMA Material used is Flexinol wire due to its high availability, well studied and documented characteristics and trainability of the material is high.

Fluid: Water is used as a test liquid

3.3 Testing Parameters

- Temperature developed along the SMA wire
- Flow rate of working fluid across the tube
- Change in tube area along the length of the tube

The dimensions of the tube and the properties of the SMA coil are shown in table 1 and table 2

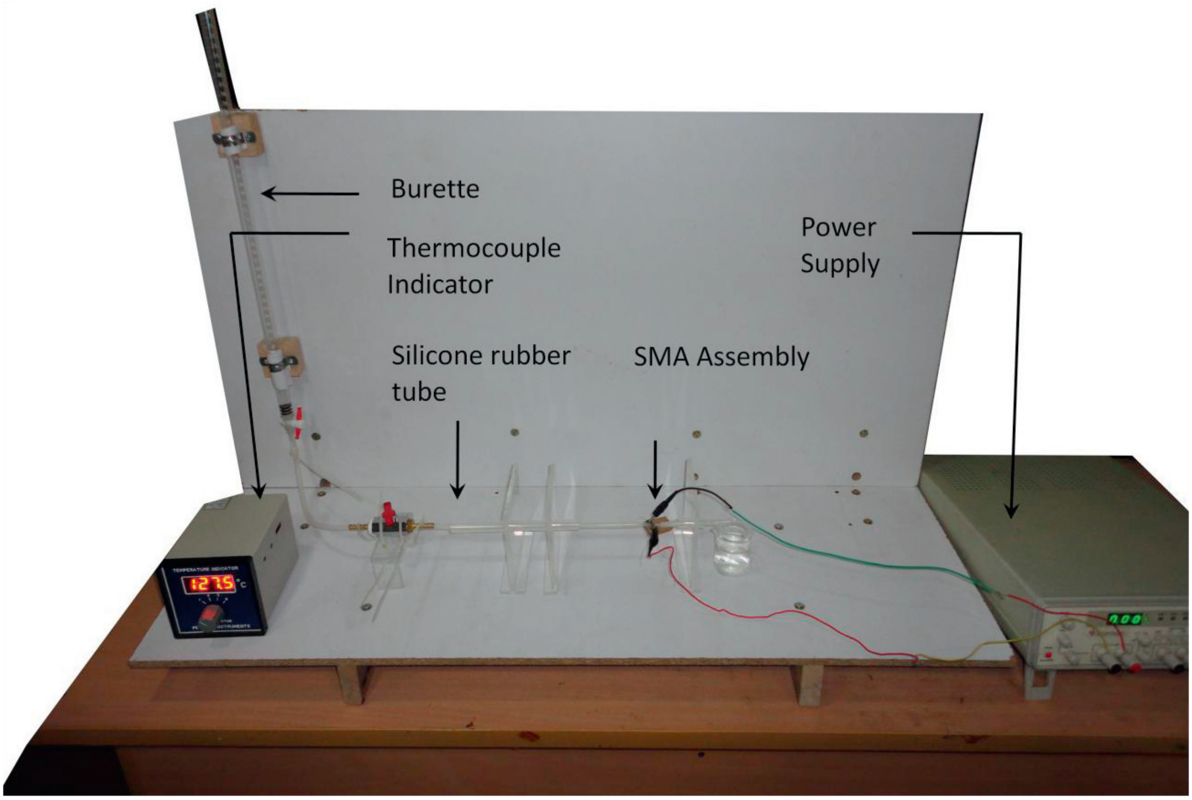


Figure 4 Experimental Setup

Table 1 Dimensions of arrangement setup

Dimension	Value
Tube inner diameter	4 mm
Tube outer diameter	5 mm
Length of tube	130 mm
SMA Coil pitch	0.01 mm
Coil diameter	0.250 mm
Number of SMA Wire	3
Number of turns	2

Table 2 SMA Material Properties

Properties	Shape Memory Muscle Wire
Type	Flexinol LT
Density	6450 kg/mm^3
Resistivity	100x10^{-6} Ωcm(Austenite)
	80x10^{-6} Ωcm(Martensite)
Young's Modulus	60 GPa
Poisson's Ratio	0.3
Coefficient of Thermal Expansion	11.0E-6/° C (Austenite)
	6.0E-6/° C (Martensite)
Thermal Conductivity	18 W/m° C(Austenite)
	8.6 W/m° C(Martensite)
Convection Coefficient	110 W/m^2

A burette is placed in the setup to provide a measured reservoir for the water which acts as the working fluid. A flow control valve is placed in the setup to regulate the flow of water inside the flexible silicone rubber tube. The flexible tube is mounted horizontally ensuring a zero head, as any minute differences would aid the flow other than the pumping device. A volume measurement device is placed at the end of the silicone rubber tube to measure the volume of fluid collected with respect to time, this measurement provides the flow rate of the working fluid by pumping.

The SMA actuator is placed at the required position and the observations are made. The SMA actuator consists of a strand of 4 SMA wires bound together to obtain increased actuation as compared to actuation by single SMA wire. The SMA wires strand occupy a width of 2 mm of surface contact on the flexible silicone rubber tube The reduction in diameter by actuation on the tube is measured using a micrometer. The heat source for the SMA wire is provided by a regulated power supply.

3.4 Temperature Measurement

A thermocouple arrangement was placed to establish the relationship between current and the temperature and the results are plotted in graph shown in figure 7. The importance of establishing this relationship is that heat is provided by electrical power source. It is therefore required to quantify the temperature developed with respect to the current passing through the SMA wire. The governing equation for heating is denoted by Equation 1 and for cooling by equation 2. The current versus temperature relationship is quantified in Equation 3[11]

$$mc_p \frac{dT}{dt} = i^2 R - hA[T - T_a] \quad \text{For Heating} \quad (1)$$

$$mc_p \frac{dT}{dt} = -hA[T - T_A] \quad \text{For Cooling} \quad (2)$$

$$i^2 = \alpha \frac{\left[[T_1 - T_a] - [T_2 - T_a] \times e^{-\left(\frac{\alpha}{\beta}\tau\right)} \right]}{1 - e^{-\left(\frac{\alpha}{\beta}\tau\right)}} \quad \text{For Heating} \quad (3)$$

where

$$\alpha = \frac{hA}{R} \quad (4)$$

$$\beta = \frac{mC_P}{R} \quad (5)$$

$$\frac{\alpha}{\beta} = \frac{hA}{mC_p} \quad (6)$$

The maximum current required for reaching the Austenite transformation temperature is obtained as 1.1658 Amps and the maximum power is calculated 19.5mW to be where the total resistance of the three wires are 0.0144 Ω/cm. The nitinol wire is fastened to the test bench used to perform analysis; the ends of the wire are attached to thermocouple leads which are a contact thermal sensor used to measure temperature at a particular point. Thermocouples cannot be directly fastened to a nitinol wire as measurements would be erroneous as the material would form another thermocouple and also there would occur eddy losses between the thermocouple and the nitinol wire.

Hence heat sink paste is applied to the ends of the thermocouple leads which act as an electrical insulator but a good thermal conductor. Since indirect measurement is performed, errors during detection of the temperature are present. The error percentage between theoretical and experimental results is plotted in the following graph represented in figure 5 Accurate temperature measurement is possible by using thin film RTD devices which could be mounted directly on the SMA wire to measure the temperature at a particular instant of time.

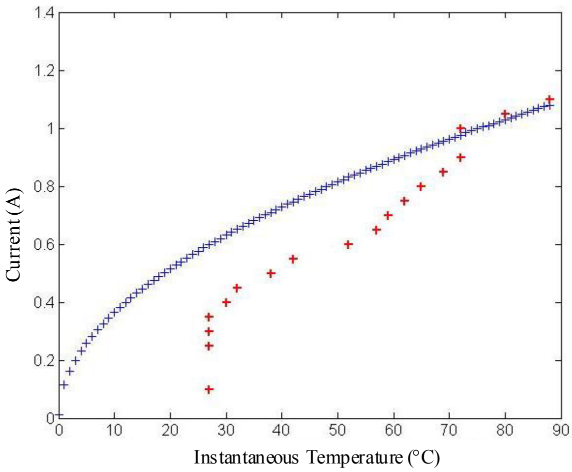


Figure 5 Current Vs Temperature across SMA wire

3.5 Fluid displacement and tube dimensions

Displacement of fluid by actuation is measured using a micrometer and examined using a microscope when the actuation of SMA wire is performed. The diameter reduction is observed to be from outer *diameter 5mm* reducing to *diameter of 4.2mm*. The amount of fluid displaced is in the micron scale where quantification of flow had become tedious. Hence with the observed real time deformation the flow rate is predicted using FEM analysis software COMSOL Multiphysics 4.2

Domain Equations:

The fluid flow is described by the incompressible Navier-Stokes equations shown in equation 4

$$\rho.\frac{\partial u}{\partial t} - \nabla.\mu(\nabla u + (\nabla u)^T) + \mu u.\nabla u + \nabla p = 0 \tag{7}$$

$\nabla .u = 0$

The volumetric flow rate at any instant *t*, is computed by a boundary integral over the pipe's inlet or outlet boundary as shown in equation 5 and equation 6

$$\dot{V}_{in} = -\int_{s_{in}} 2\Pi r(n.u)ds \tag{8}$$

$$\dot{V}_{out} = -\int_{s_{out}} 2\Pi r(n.u)ds \tag{9}$$

The material for the tube is considered as silicone rubber whose material properties are as shown in table 3 and the input fluid is considered as water of standard built in properties. The analysis parameters for the fluid flow are shown in table 4.

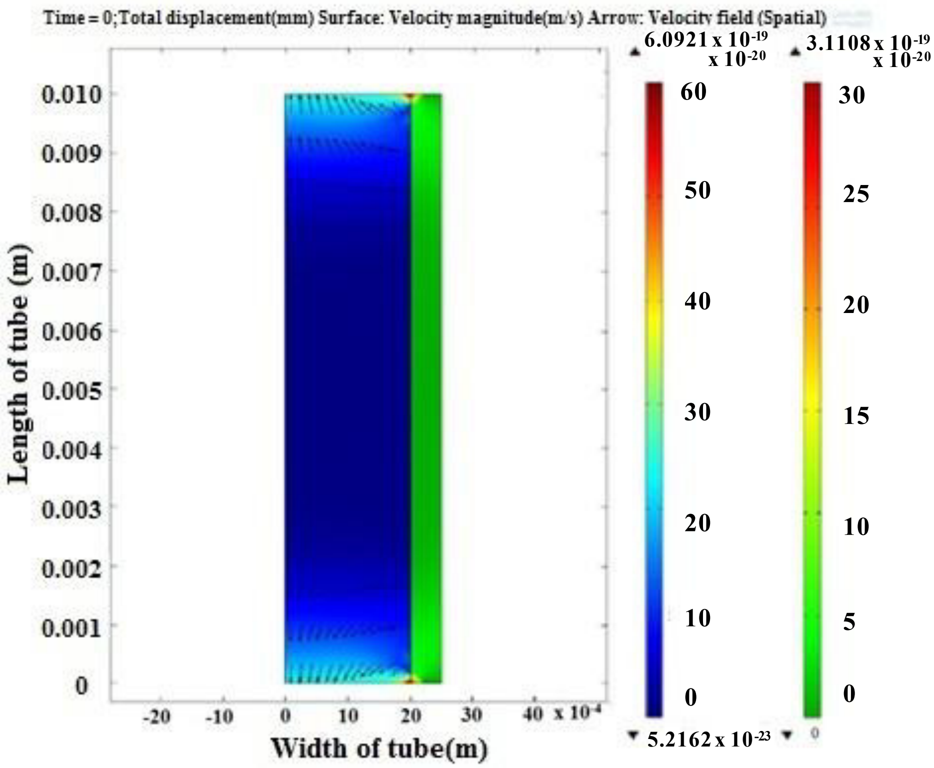
Table 3 Material Properties of Silicone Rubber

Property	Silicone Rubber
Density(ρ)	1100 kg/m^3
Young's Modulus(E)	0.05 GPa
Poisson's Ratio(υ)	.33
Heat Constant at constant pressure(Cp)	1300 J/(kg*K)
Relative Permittivity(ϵ)	4
Coefficient of Thermal Expansion(α)	250e-6 [1/K]
Thermal Conductivity(k)	0.20 W/(m*K)

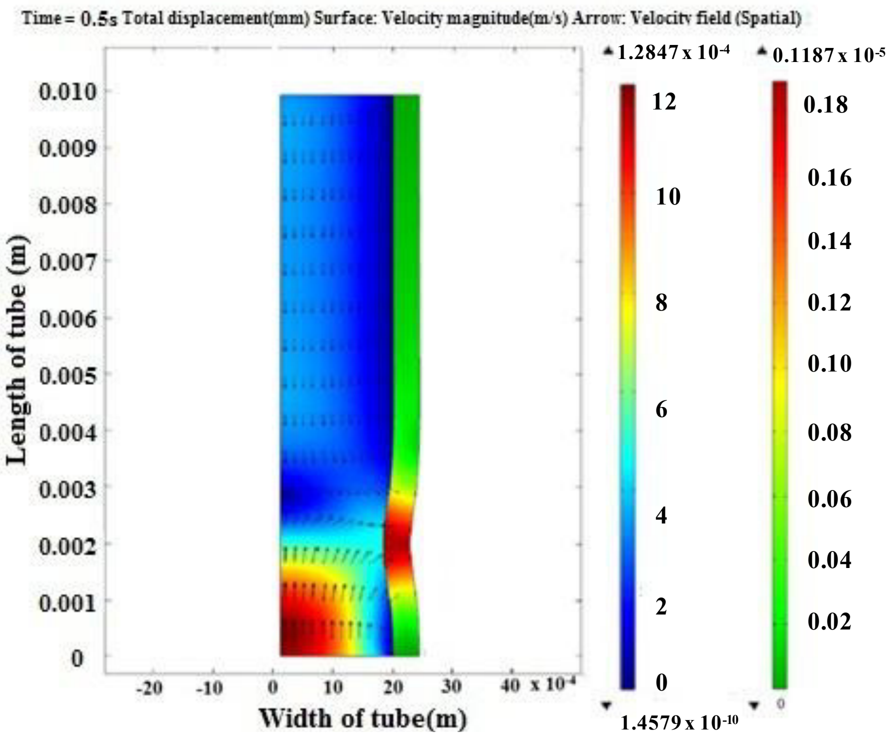
Table 4 Analysis Parameters

Parameter	Value
Load applied time	0.3 s
Load release time	1.2 s
Time to reach maximum load	0.75 s
Load coordinate from base	0.002 m
Force application width	2e-4 m
Total time for a pump cycle	1.5 s
Maximum deformation	0.8 mm

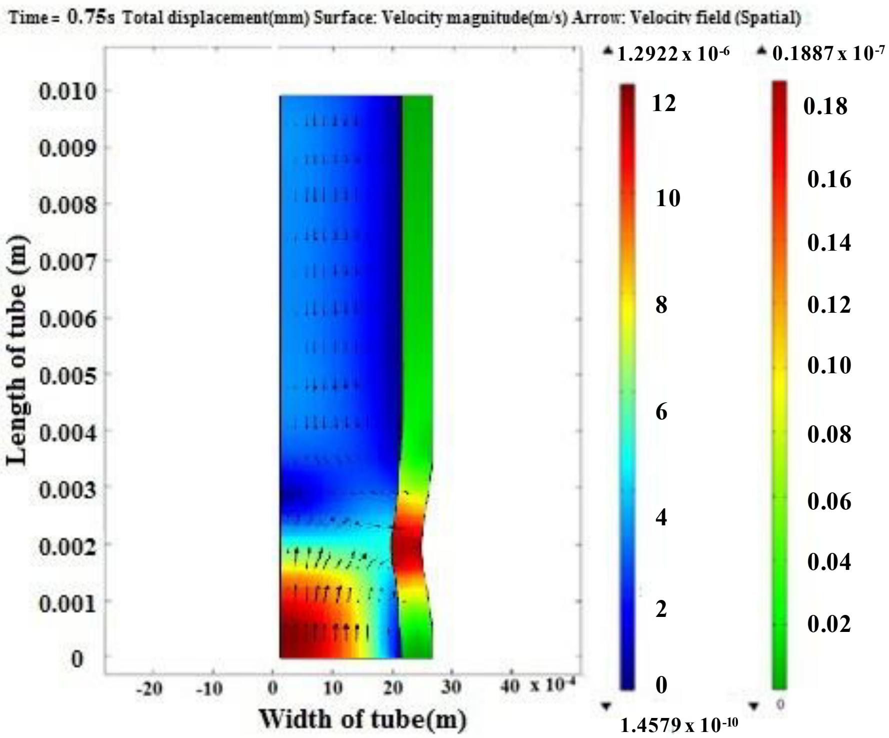
A 2D Axisymmetric model is considered for the modelling of the interaction domain since the flexible tube is a symmetric structure. Performing axisymmetric analysis reduces the computation time than analysis of 3D structure.
The inner diameter of tube is considered as 4×10^{-3}m and outer diameter as 5×10^{-3}m.The fluid medium is considered as incompressible flow and the solid model is considered as linearly elastic model. The flow along the tube is considered as laminar flow. A prescribed mesh displacement , arbitrary Lagrangian-Eulerian (ALE) technique handles the dynamics of the deforming geometry and the moving boundaries with a moving grid The integration point is set between the lower end of the tube where z = 0m to z = 0.01m. The results of deformation are plotted in Figure 6 for various time intervals.



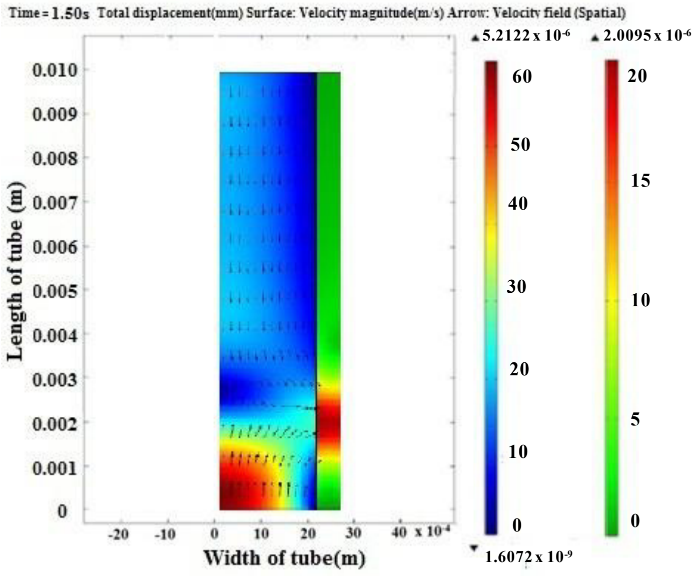
(a)


Time = 0.5s Total displacement(mm) Surface: Velocity magnitude(m/s) Arrow: Velocity field (Spatial)
Length of tube (m)
Width of tube(m)
x 10⁻⁴
1.2847 x 10⁻⁴
0.1187 x 10⁻⁵
1.4579 x 10⁻¹⁰

(b)


Time = 0.75s Total displacement(mm) Surface: Velocity magnitude(m/s) Arrow: Velocity field (Spatial)
Length of tube (m)
Width of tube(m)
x 10⁻⁴
1.2922 x 10⁻⁶
0.1887 x 10⁻⁷
1.4579 x 10⁻¹⁰

(c)



(d)

Figure 6 (a) Load applied at t = 0 s; (b) t = 0.5 s; (c) t = 0.75 s; (d) t = 1.5 s

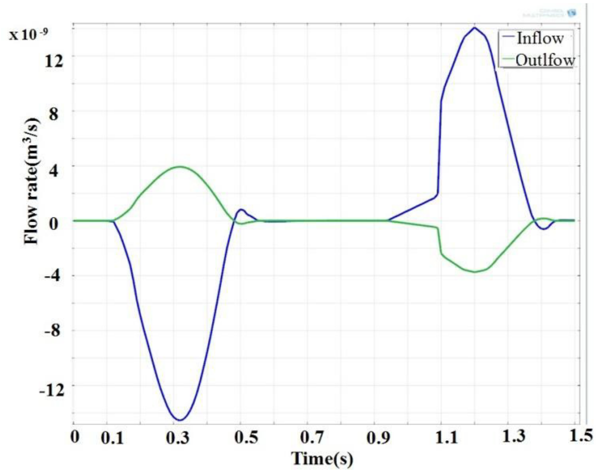


Figure 7 Inlet flow and Outlet flow from tube

The graph in figure 7 shows that deformation of 0.8 mm in the silicone rubber tube causes an initial rise in the outlet flow in the tube during the actuation period. It attains a maximum of 3.92 x 10^{-9} m^3/s outlet flow which gradually decreases and stabilises when the actuation force is released. There occurs a dip in the inlet flow during actuation as there occurs backflow into the inlet area which causes resistance to flow which results in reduced inlet flow duing actuation of the tube and when the actuation is completely relieved the inlet flow gains a maximum of 13 x 10^{-9} m^3/s. This is attained before the completion of the clamping force. And the reduction in the volume of 1.02 x $10^{-8}m^3$ of maximum volume reduction is observed in the actuation process which is shown in figure 8.

As a result the accumulated flow in the tube is computed which acts as the important parameter to measure the efficieny of the pump where the graph in figure 9 measure the netflow in the system from which the accumulated or net pumped fluid is derived. It is observed that there is a positive accumulated flow in the system which denotes positive displacement of water by pumping.The initial flow diagram shows excessive backflow in the process of actuation which depletes the pumping output. The overall study can be extended by testing with multiple sets of SMA bundle coil. This when placed would result in continuous movement of fluid in one direction. Hence an actuation firing order would be created for optimal flow of fluid with minimum backflow.

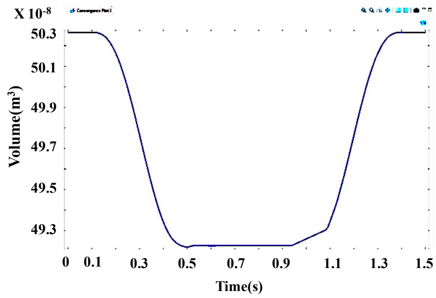


Figure 8 Volume reduction inside the tube

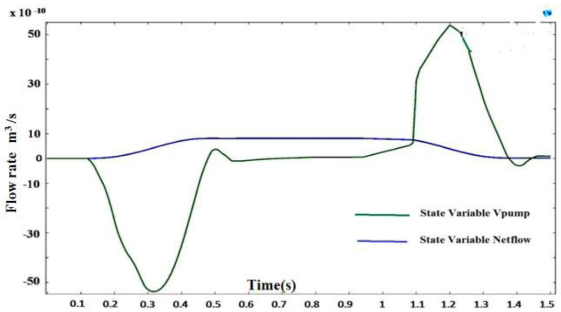


Figure 9 Accumulated flow and net flow

4. Conclusion and Scope for future work

The following conclusions could be drawn from the above investigation and experimentation process where the concept of a miniature flexible flow pump concept was proposed. Various preliminary investigations were carried out to narrow down the methodology of the working principle based on compactness and simplicity factors. Experimental analysis was carried to build a prototype and analyse the actuating parameters. The number of SMA wires needed to be bundled for considerable actuation was investigated and implemented in the prototype. The area reduction that is possible by the actuation is observed and measured. The deformation values were fed into the FEM software to analyse the pumping flow capability of the SMA wire on the flexible silicone rubber tube. Various results of accumulated flow and volume reduction were calculated based on FEM analysis which resulted in a positive output where there occurred a positive net displacement of water by the actuation represented by the Volume flow variable. Future work aims at experimentally analysing the volume flow and velocity of fluid after actuation using Doppler ultrasound scanner and to build multi module SMA wire bundle to observe net displacement and hence comparing those with FEM results.

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