Design of a Valveless Micro-Pump for Variable Rate of Insulin Delivery

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Abstract

Objectives: Unlike conventional micro-pumps which have valves that fail as they keep flapping twice during each pumping cycle and a separate micro-needle array, through which drug is injected. The design here uses a micro-pump without moving valves and with the micro-needles integrated with the micro-pump itself. Method/Statistical Analysis: The dimensions for the micro-pump and the micro-needles are chosen based on the physical characteristics of the fluid that needs to be pumped (in this case insulin density, viscosity, size of the particles in the fluid etc). The model is constructed and simulated using COMSOL multi-physics software. Findings: The model is simulated to check the volume of liquid pumped during each cycle and to see if the model constructed remains stable when potential is applied to the actuating membrane. The simulation results showed that the micro-pump model constructed is stable under various levels of applied potential (+200V to -200V), results of which are presented in the following sections. It was also observed that the dead volume of fluid that is left in the pumping chamber is less as compared to the conventional model. Application/Improvement: This micro-pump was designed especially for insulin delivery. The actuation method being piezo-electric, the volume of fluid pumped can be altered by varying the frequency of the applied potential or the amplitude of the applied voltage. This model can still be improved if it can be integrated with a glucose sensor. Based on the level of the glucose measured the insulin to be delivered can be altered.

Keywords: Diffuser, Micro Pump, Micro Needles, Nozzle, Piezo-Electric Actuator, Valveless

1. Introduction

Delivery of insulin typically must be altered depending on the level of glucose level in blood. Typically for a diabetic patient blood glucose level can vary at different times of a day. Therefore, blood glucose need to be monitored at regular intervals of time, and depending on the glucose level the amount of insulin delivered needs to be altered. This is possible with a micro-pump with a piezo-electric membrane, which acts as the actuator. The rate of delivery of insulin can be altered by altering the frequency at which the membrane moves.

Because the micro-pump needs to deliver insulin over an entire day (over twelve hours), it needs to have very low dead volume. There should be no residual drug left in the pump just circulating in the pump without getting delivered. The micro-pump with piezo-electric actuator presented here, not only offers variable delivery rate, but also ensures that the dead volume is reduced to a minimum. Dead volume is the volume of fluid left over in the pump without getting pushed out. The PZT membrane acts as the actuator which draws the insulin from the reservoir into the pumping chamber and from the pumping chamber pumps the insulin into the body through the micro needles. The micro needles are integrated with the micro-pump in this model and hence eliminate the need for micro channels and this makes the size compact.

Figure 1 a. Nozzle.
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2. Structure Design of the Micro-Pump used in Numerical Simulation

Piezoelectric effect is a reversible physical phenomenon. That means an applied voltage, across the face of the piezo-electric material produces a mechanical strain. This causes a deformation in the piezoelectric material. The magnitude of this piezoelectric polarization is represented by $P$, in terms of axial stress $\sigma$

$$P = P_{xx} + P_{yy} + P_{zz}$$

Where,

$$P_{xx} = d_{11}a_{xx} + d_{12}a_{yy} + d_{13}a_{zz}$$

$$P_{yy} = d_{21}a_{xx} + d_{22}a_{yy} + d_{23}a_{zz}$$

$$P_{zz} = d_{31}a_{xx} + d_{32}a_{yy} + d_{33}a_{zz}$$

Where $d_{mn}$ are piezoelectric coefficients along the orthogonal axes of the crystal cut in Coulomb/Newton.

Earlier models of micro-pumps used for drug delivery used electrostatic actuation both for the membrane as well as valves. These valves used piezoelectric bimorphs. These bimorphs were fully immersed or at least partially exposed to the fluids being pumped. Therefore they have to be coated with a dielectric material to avoid electrical short circuit. Further these valves keep flapping at frequency of 1 kHz. Therefore these valves breakdown. Hence passive valves are used here. The principle of operation of the valves in this pump is the difference between pressure losses in different kinds of accessories. The nozzle and diffuser are considered accessories. The way the accessory behaves either as a diffuser or a nozzle, only depends on the direction of flow at each instant. So each nozzle or diffuser accessory behaves as a nozzle when the direction of flow is as shown in Figure 1a., and like a diffuser when the flow direction is as shown in Figure 1b.

The proposed micro-pump structure consists of a piezoelectric membrane PZT -5A of thickness 2µm, of length 400µm and width 400µm, supported around its edges by a region 10µm wide. The piezo-electric membrane is coated on either side by a layer of Silicon di Oxide SiO2 of thickness 1µm. The membrane rests on the pumping chamber of length 480µm, width 380µm and height 150µm. The inside of the pumping chamber is inverted pyramid shaped, with the sides sloping towards the centre, which has the outlet. On the side of the piezo-electric actuator membrane lies the inlet. The shape of the outlet and inlet are such that one acts as a nozzle and the other acts as diffuser. Below the pumping chamber is another chamber with an array of 20 micro-needles (4 rows with 5 micro-needles in each row). The micro-needles are cone shaped with base diameter of 80µm and height of 100µm with a cylindrical bore slightly off centre with a diameter of 10µm.

The structure is as shown in Figure 2. When a positive potential is applied to the piezoelectric membrane the membrane bends upwards and fluid flows into the pumping chamber. When the applied potential is reversed, the membrane bends downwards, pumping out liquid equal to the bent volume of the membrane. The chamber volume inside the micro pump is thus changed alternatively every half cycle by periodical switching of applied voltage. The various dimensions of the micro pump that is simulated are given below in Table1.

![Figure 2. 3-Dimensional Model of the micro-pump used in simulation.](image)

| S. No | Structure       | Dimension in µm |
|-------|-----------------|-----------------|
| 1.    | Pumping Chamber:|                 |
|       | Length          | 480             |
|       | Breadth         | 380             |
|       | Height          | 150             |
### 3. Simulation using COMSOL Multiphysics

The model is constructed using COMSOL Multiphysics and simulation is carried out for various applied voltages. Grid independent study is carried out to study the effect of the applied potential at various grid sizes.

#### 3.1 Equations, Materials and Boundary Conditions

The piezoelectric material used for the actuating membrane is PZT-5A. Voltage is applied to this membrane which acts as the actuator. For PZT-5A, the compliance matrix, piezoelectric coupling matrix and relative permittivity matrix are

\[
\begin{bmatrix}
15.4 & -5.74 & -7.22 \\
-5.74 & 16.4 & -7.22 \\
-7.22 & -7.22 & 18.8
\end{bmatrix}
\times 10^{-14} \text{m}^2/\text{N} \\
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\times 10^{-12} \text{C/N} \\
\begin{bmatrix}
1730 & 0 & 0 \\
0 & 1730 & 0 \\
0 & 0 & 1730
\end{bmatrix}
\]

The electric field as result of the applied voltage creates a longitudinal strain along the Z axis, the magnitude of which is given by

\[
S_1 = E_2 d_{31}
\]  

As a result the PZT membrane curves into an arc, the radius of curvature of which is proportional to the applied voltage. Volume of fluid pumped in one cycle is approximately given by

\[
V = \frac{1}{6} \pi (3a^2 + h)
\]

where, ‘h’ is the displacement of the membrane from its original position due the applied voltage and ‘a’ width of the PZT membrane.

#### 3.2 Meshing and Solving Strategy

The rate at which fluid flows out of the pump is determined as a surface integral of fluid velocity. To determine the fluid volume flow of the micro-pump, the fluid flow rate is integrated again over a period of time. Unless meshing is chosen carefully, simulation yields inaccurate results. Using fine meshing results in a very large number of elements, but yield accurate results.

![Figure 3. Meshed 3-D model of the micro-pump that is simulated.](image)

The size of computer RAM and the computational time limits the mesh size. Therefore we choose the mesh size without compromising too much on the accuracy. The result of meshing is presented in Figure 3. The final mesh consists of 1, 86, 258 pyramids, tetrahedral and prisms.

### 4. Results

Typical results of simulation of the deformation of the piezoelectric membrane for an applied voltage of +20V
and -20V are presented in Figure 4 and Figure 5 respectively.

Maximum displacement occurs at the centre of the membrane. The outlet nozzle is positioned in such a way (at the base of the inverted cone shaped chamber) that any residual volume of fluid that remains at the end of the last pumping cycle gets pumped out first in the following cycle.

The deformation and displacement of the membrane from its initial position depends on the magnitude and polarity of the applied voltage. A detailed plot of displacement Vs applied voltage is presented in Figure 6.

Further results of simulation are presented in Figure 7 and Figure 8.

**Figure 4.** Displacement of the PZT membrane for applied voltage of +20V.

**Figure 5.** Displacement of the PZT membrane for applied voltage of -20V.

**Figure 6.** Plot of Displacement of PZT Membrane Vs Applied Voltage.

**Figure 7.** Surface: Total Displacement (µm) Arrow Volume: Electric Field (Spatial)
Volume: Total Displacement (µm) Arrow Volume: Electric Field (Spatial).

**Figure 8.** Slice: Electric Potential (V) Volume : Electric Potential
Surface: Electric Potential(V) : Line Electric Potential Arrow Volume: Electrical Field (Spatial) Slice Electric Potential(V).
5. Conclusion

A micro-pump integrated with an array of micro needles was analyzed using numerical simulation. These pumps, due to their compact size and the fact that they can be integrated with an array of micro needles mean that these can be used in portable or wearable devices for drug delivery like insulin throughout the day. The design also ensures there will be very little residual drug left. Hence this micro-pump need not be replaced every day, which will be the case if there is residual drug left over in the pump without getting pumped out at all. Although voltages as high as 200V were applied during simulation even lower voltages in the range of 20V produces an appreciable displacement which can effectively pump fluids.

6. References

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