Comparison of Piezo-material based Energy Transduction Systems for Artificial Nanoswimmer

S Nain1, J S Rathore1* and N N Sharma2

1Department of Mechanical Engineering, BITS Pilani, Rajasthan, India 333031
2School of Automobiles, Mechanical & Mechatronics, Manipal University, Jaipur 303007, India
*Corresponding Author E-mail: jitendarathore@pilani.bits-pilani.ac.in

Abstract. The energy harnessing is a process of obtaining energy from the surrounding environment and converting into electrical energy. In the last two decades, there has been a plenteous study in energy harnessing. Now a day, energy harnessing using piezoelectric materials has drawn attention of researchers due to low cost, flexibility and light weight. The benefits of piezoelectric material can be utilized by designing a self-powered device for artificial nanoswimmer. Some of the ceramics which displays the piezoelectric effect are lead-zirconate-titanate (PZT), lead-titanate (PbTiO2), lead-zirconate (PbZrO3) and Barium Titanate (BaTiO3). PZT is most extensively used piezoelectric material in the field of energy harnessing but it is brittle in nature. Lead based piezoelectric materials are toxic in nature and may not suitable for in-vivo biomedical applications. To eradicate this problem, researchers are interested in synthesizing lead free piezoelectric material such as Aluminium Nitride (AIN), Barium Titanate (BaTiO3) and Polyvinylidenefluoride (PVDF). The biocompatibility of PVDF makes it appropriate to be used for energy harnessing in human body for applications like on board powering of nanoswimmer for various disease detection and drug delivery. In this paper, a cantilever beam is being simulated in COMSOL to study electric potential generated on the surface of beam made of different piezoelectric materials such as AIN, PVDF and PZT due to fluidic pressure, which will be utilized as energy for actuation of artificial nanoswimmer. Piezo-based cantilever beams have been compared and maximum electric potential is being observed in PVDF based beam. PVDF seems most promising piezoelectric material for in-vivo biomedical application and it is readily available.

Keywords: Energy harnessing, Piezoelectric, PVDF, Nanoswimmer.

1. Introduction

Recent advancement in the field of nanotechnology enables to fabricate and design smaller nanomachines such as nanorobots which are capable of doing lots of task like repair of cells, nanosurgery [1], targeted drug delivery [2] and nano dentistry [3]. The engrossment of nanorobots for various activities necessitates four fields: (a) energy storage, (b) energy transduction (c) control and (d) transmission [4]. Scientists and engineers are mimicking natural biological bacteria such as E. coli, Paramecium for their design and fabrications of machines at nano levels. Researchers [5]-[8] are also imitating the mode of propulsion (planar and helical) exhibit by natural bioorganisms and investigated it theoretically. To propel artificial nanoswimmer, different propulsion mechanisms are being developed till date like chemical
actuation [9]-[10], magnetic actuation [11]-[12], ultrasonic actuation, thermal actuation mechanism [13]-[14] and bacterial actuation mechanism [15]. Each and every actuation mechanism has some pros and cons [16], so the alternative of propulsion of an artificial nanoswimmer inside the human body is required. For propelling nanoswimmer inside the human body, the selection of material has vital importance in fabricating nanoswimmer. Mechanical energy from the surrounding environment is being transduced in the form of electrical energy by electrostatic, electromagnetic and piezoelectric means. Piezoelectric technique seems more promising conversion technique because it requires piezoelectric materials to convert mechanical pressure or displacement directly in the form of electrical voltage. In present study, three different piezoelectric materials are explored and their performance are compared on the basis of induced stress and voltage generation capacity for enhanced energy transduction system for an artificial nanoswimmer in fluid domain.

2. Energy harvester generators and different piezoelectric materials

Energy transduction is the essential component in designing of nanorobots. Energy is classified in numerous ways such as mechanical, electrical, light, heat and chemical. Among various kinds of energy, electricity is the most commonly used form because of it simply transformation into other types of energy. The term “Powering” generally implies conversion of any other form of energy into electrical energy. The most commonly used mechanism for conversion of mechanical energy into electrical energy are electrostatic [17], piezoelectric [18], and electromagnetic [19]. The application of electromagnetic and electrostatic mechanisms as energy harvesting purpose possesses some limitation [20]-[21]. The electromagnetic harvesters are larger in size which makes them impracticable to be used in MEMS [20]. It remains a challenge to design and fabricate an electromagnetic energy harvester in micro domain due to poor properties of magnet and coil. Electrodes are used as parallel plate capacitor in electrostatic energy harvester, which needs to be charge initially to start the conversion process [21]. In 1880, Jacques and Pierre Curie observed the effect of piezoelectricity. Piezoelectricity is the innate characteristics of the certain piezo-materials which makes it suitable for alternative energy harvester. The property of piezoelectric material such as conversion of ambient vibration into electrical form gained attentions of many researchers because it does not require any external power supply and can be useful in MEMS domain [22]. Piezoelectric generators have many advantages such as the mechanical energy required for conversion can be achieved from the environment, low cost, flexible and light weight. All these benefits of piezoelectric material can be utilized by designing a self-powered device for artificial nanoswimmer. Piezo-energy generators at micron scale have huge scope for research and applications in the today’s world. Piezo-energy generators are classified as direct and inverse piezoelectric generator. In direct piezoelectric energy harvester, mechanical strain is converted into electric potential while in case of inverse piezoelectric generator electric potential is applied as input which has been converted into mechanical strain as shown in Figure 1.

![Figure 1. Schematic of direct and inverse piezoelectric effect.](image-url)
Some of the ceramics which displays the piezoelectric effect are lead-zirconate-titanate (PZT), lead-titanate (PbTiO2), lead-zirconate (PbZrO3), and barium-titanate (BaTiO3). PZT is the most frequently used piezoelectric ceramic because of high electromechanical coupling ability. However, PZT is an extremely brittle material and hence this presents limitations to the strain [23]. Polyvinylidenefluoride (PVDF) is another commonly used piezoelectric polymer which is flexible and can be employed in energy harvesting applications [22]. Over the last few years, ZnO, piezo-ceramics such as PZT and piezoelectric polymers (PVDF) have been used for designing micro and nano systems [24]. PZT has low energy conversion efficiency [25] and it is fragile as compared to PVDF [26]-[27] which makes it unsuitable to produce energy in alternating loads while PVDF is flexible, light weight, biocompatible inexpensive [28]. Lead based piezoelectric materials are second alternative for energy harvesting but lead is a toxic material which may leave negative impression on the environment. Scientists are interested in synthesizing lead free piezoelectric material [29] and have developed the more flexible piezoelectric material. PVDF (polyvinylidenefluoride), can be used in various applications of energy harnessing. Piezoelectric materials can stand high strain, which leads to conversion of more mechanical energy into electrical energy. The biocompatible property [30] of PVDF makes it appropriate to be used for energy harnessing in human body for various applications like on board powering of nanoswimmer for various disease detection and drug delivery.

Cantilever beam structure is more attractive for energy harvesting purpose because of low resonance frequency and high average strain for a given applied force. The output of piezo-harvester can be controlled by changing the cantilever sensitivity. Researchers have increased the sensitivity of cantilever by changing the shape and dimensions [31]. The energy harnessing device for nanoswimmer is simulated using COMSOL to see the effect of different piezoelectric materials on the electric potential induced.

### 3. Design and Simulation

The COMSOL simulation of cantilever beam with different piezoelectric materials is explored for energy transduction system of an artificial nanoswimmer. The properties of piezoelectric materials PVDF, PZT and AIN are shown in Table 1. For simulation the geometric dimensions for piezoelectric cantilever beams are length 50µm, width 2.5µm and thickness 2.5µm.

| Material Properties | PVDF | PZT | AIN |
|---------------------|------|-----|-----|
| Young’s Modulus (GPa) | 2    | 43  | 302 |
| Density (kg.m⁻³)    | 1780 | 7500| 3300|
| Poisson’s ratio      | 0.3  | 0.34| 0.23|

The beam is fixed at one end and is representing *Paramecium*. The fluid velocity is chosen in the range of velocity 50µm.sec⁻¹ to 80µm.sec⁻¹ to maintain laminar flow and a low Reynolds number regime. The simulations are carried out in COMSOL multiphysics 5.2@. Three physics namely, Fluid structure interaction (FSI), Piezoelectric and Electrostatic, are coupled with each other to study the effect of fluid velocity on beam in terms of stress and electric potential for different materials. The laminar fluid flow is maintained in the container of size 300µmx150µmx150µm in which piezoelectric beam is placed. The velocity of liquid will leads to generation of stress on the cantilever beam which in turns develops voltage on the beam due to fluidic pressure. The
displacement ‘\(D\)’ of beam depends upon the geometric parameters of cantilever beam and properties of material as shown in equation 1 [32].

\[
D = \frac{3\sigma(1 - \vartheta)L^2}{YT^2}
\]  

(1)

Where ‘\(\sigma\)’ is the stress generated on beam, ‘\(\vartheta\)’ is Poisson’s ratio, ‘\(Y\)’ is Young’s modulus, ‘\(L\)’ is the beam length and ‘\(T\)’ is the cantilever thickness.

To study the voltage generation, fluidic pressure developed on polymer surface is defined as boundary load in piezoelectric module. The lower surface of the beam is grounded and floating potential on the upper surface is applied to see the effect of fluid flow on piezoelectric beam. The model is meshed with physics controlled mesh with element size normal. The average von Mises stress generated on the beam is within the permissible limit of materials for AIN, PZT and PVDF. The allowable stresses (\(\sigma_{\text{all}}\)) approximately 302, 43 and 2GPa for AIN, PZT and PVDF respectively.

4. Results and Discussion

To examine the performance of energy harnessing using piezoelectric material three conditions are applied; first, same unimorph (single layer of piezoelectric material) structure, second same volume of material and third is same velocity fluid flow is considered for simulation. Results for AIN, PVDF and PZT piezoelectric material follows same trend for voltage generation on the upper surface towards the fixed end of the beam with respect to velocity as shown in Figure 2.

![Figure 2](image)

**Figure 2.** Comparison of Electric potential generated on piezoelectric beam with different materials.

The three dimensional (3D) model of piezo based nanoswimmer is designed and simulated in COMSOL. The average von Mises stress for AIN, PVDF and PZT is approximately 74Nm\(^{-2}\), which is well below the allowable stress of materials. The electric potential is observed maximum about 188 nV for PVDF based nanoswimmer in comparison to AIN and PZT. PZT is lead based material and is not biocompatible. PVDF is biocompatible and also suitable for in-vivo application. The variations in geometric parameters such as width and thickness of beam model
are affecting the output electric voltage as shown in Figure 3 and Figure 4. In the available literature, 2.9 mV electric potential is generated on piezoelectric cantilever beam in fluid domain at velocity 5 ms\(^{-1}\) \cite{33}.

It is observed from the simulation as width of beam increases electrical potential decreases while if thickness increases electric potential will increase. The length is kept constant for all the model of piezo based nanoswimmer. The width and thickness is varied to see their effect on electric potential. From the Figure 4a, 4b and 4c, a linear relationship is observed between voltage and thickness. It is showing quite promising results. In Figure 3, width of beam has been increased from 1.25\(\mu\)m to 2.5\(\mu\)m while keeping thickness of beam constant. Maximum electric potential 33.1\(nV\) is observed for PVDF based cantilever beam, when width of beam is 1.25\(\mu\)m. Maximum enhancement in electric potential is 43\% when width is decreasing from 2.5\(\mu\)m to 1.25\(\mu\)m for PVDF cantilever beam. Linear trend has been followed on increasing thickness for cantilever beam made of AIN, PZT and PVDF in Figure 4. Maximum electric potential around 187.5\(nV\) has been noticed for PVDF piezoelectric cantilever on increasing thickness from 1.25\(\mu\)m to 2.5\(\mu\)m. Due to thickness variation from 1.25\(\mu\)m to 2.5\(\mu\)m, electric potential increase by 66\% for PVDF cantilever beam.

![Figure 3](image-url)

**Figure 3.** Effect on electrical potential observed for AIN, PZT and PVDF by varying the width (a), (b) and (c) of piezoelectric cantilever beam.
Figure 4. Effect on electrical potential observed for AIN, PZT and PVDF by varying thickness (a), (b) and (c) of cantilever beam.

5. Conclusion
The simulation study is being performed on unimorph cantilever design in COMSOL for electric potential generation using three different piezoelectric materials. The dimensions of cantilever based artificial nanoswimmer are taken to emulate the natural bacteria. The enhanced electric potential observed for PVDF around 188nV in comparison with AIN and PZT. The conventional energy harvester such as electrostatic method require external voltage source and electromagnetic energy conversion technique needs to incorporate moving parts and provide very low output in terms of voltage. Piezoelectric based energy harnessing for artificial nanoswimmer neither involve external voltage source nor any moving parts for conversion. Effect of variations in width and thickness has been taken into consideration to enhance the electric potential. Increase in potential up to 44% has been observed by decreasing width from 2.5µm to 1.25µm while on increasing thickness from 1.25µm to 2.5µm, 66% more potential has been noticed for PVDF cantilever beam. PVDF seems most suitable piezoelectric material to study further for investigations of different deigns of energy harnessing schemes for an artificial nanoswimmer. Branching effect of cantilever beam needs to be explored to mimic natural bacteria for harnessing on-board energy for an artificial nanoswimmer.
Acknowledgment

The authors would like to acknowledge the NNMDC MEMS lab, BITS Pilani, Rajasthan India to carry out simulation in COMSOL multiphysics 5.2®.

References

[1] Shinob M C and College R E 2012 Replacement Of Heart Bypass Surgery By Nanorobots Int. J. Adv. Res. Technol. 2 119–22
[2] Freitas R A 2006 Pharmacytes: An Ideal Vehicle for Targeted Drug Delivery J. Nanosci. Nanotechnol. 6 2769–75
[3] Freitas R A 2000 Nanodontistry J. Am. Dent. Assoc. 131 1559–65
[4] Rathore J S and Sharma N N 2010 Engineering nanorobots: chronology of modeling flagellar propulsion J. Nanotechnol. Eng. Med. 1 31001
[5] Hancock G J 1953 The self-propulsion of microscopic organisms through liquids Proc. R. Soc. London. Ser. A. Math. Phys. Sci. 217 96–121
[6] Deepak K., Rathore J S and Sharma N N 2011 Nanorobot propulsion using helical elastic filaments at low Reynolds numbers J. Nanotechnol. Eng. Med. 2 11009
[7] Kotesa R S, Rathore J S and Sharma N N 2013 Tapered Flagellated Nanoswimmer: Comparison of Helical Wave and Planar Wave Propulsion Biomicrofluidics 3 343–47
[8] Rathore J S, Majumdar R and Sharma N N 2012 Planar wave propagation through a tapered flagellated nanoswimmer Nanotechnology, IEEE Trans. 11 1117–21
[9] Loget G and Kuhn A 2011 Electric field-induced chemical locomotion of conducting objects Nat. Commun. 2 535
[10] Lugli F, Brini E and Zerbetto F 2011 Shape governs the motion of chemically propelled janus swimmers J. Phys. C 116 592–98
[11] Mair L O et al. 2011 Highly controllable near-surface swimming of magnetic Janus nanorods: application to payload capture and manipulation J. Phys. D. Appl. Phys. 44 125001
[12] Wang L, Xu H, Zhai W, Huang B and Rong W 2017 Design and Characterization of Magnetically Actuated Helical Swimmers at Submillimeter-scale J. Bionic Eng. 14 26–33
[13] Wang X, Song J, Liu J and Wang Z L 2007 Direct-current nanogenerator driven by ultrasonic waves Science 316 102–105
[14] Sul O J, Falvo M R, Taylor II R M, Washburn S and Superfine R 2006 Thermally actuated untethered impact-driven locomotive microdevices Appl. Phys. Lett. 89 203512
[15] Zhang L et al. 2009 Characterizing the swimming properties of artificial bacterial flagella Nano Lett. 9 3663–67
[16] Nain S and Sharma N N 2015 Propulsion of an artificial nanoswimmer: a comprehensive review Front. Life Sci. 8 2–17
[17] Mitcheson P D, Miao P, Stark B H, Yeatman E M, Holmes A S and Green T C 2004 MEMS electrostatic micropower generator for low frequency operation Sensors Actuators A Phys. 115 523–29
[18] Truitt A and Mahmoodi S N 2013 A review on active wind energy harvesting designs Int. J. Precis. Eng. Manuf. 14 1667–75
[19] Arnold D P 2007 Review of microscale magnetic power generation IEEE Trans. Magn. 43 3940–51
[20] Beeby S P, Tudor M J and White N M 2006 Energy harvesting vibration sources for microsystems applications Meas. Sci. Technol. 17 175
[21] Roundy S, Wright P K and Rabaey J 2003 A study of low level vibrations as a power source for wireless sensor nodes Comput. Commun. 26 1131-44
[22] Sodano H A, Inman D J and Park G 2005 Generation and storage of electricity from power harvesting devices J. Intell. Mater. Syst. Struct. 16 67–75
[23] Anton S R and Sodano H A 2007 A review of power harvesting using piezoelectric materials (2003–2006) Smart Mater. Struct. 16 R1
[24] Gao Y and Wang Z L 2007 Electrostatic potential in a bent piezoelectric nanowire. The fundamental theory of nanogenerator and nanopiezotronics Nano Lett. 7 2499–505
[25] Chang C, Tran V H, Wang J, Fuh Y K and Lin L 2010 Direct-write piezoelectric polymeric nanogenerator with high energy conversion efficiency Nano Lett. 10 726–31
[26] Fang J, Wang X and Lin T 2011 Electrical power generator from randomly oriented electrospun poly (vinylidene fluoride) nanofibre membranes J. Mater. Chem. 21 11088–91

[27] Dakua I and Afzulpurkar N 2013 Piezoelectric energy generation and harvesting at the nano-scale: materials and devices Nanomater. Nanotechnol. 3 21

[28] Mohammadi F, Khan A and Cass R B 2003 Power generation from piezoelectric lead zirconate titanate fiber composites in Materials Research Society Symposium Proceedings 736 263–270.

[29] Kumar A, Sharma A, Kumar R, Vaish R and Chauhan V S 2014 Finite element analysis of vibration energy harvesting using lead-free piezoelectric materials: A comparative study J. Asian Ceram. Soc. 2 138–143

[30] Majumdar R, Singh N, Rathore J S, and Sharma N N 2013 In search of materials for artificial flagella of nanoswimmers J. Mater. Sci. 48 240–250

[31] Johnny H H E and Li Y F 2006 High sensitivity piezoresistive cantilever sensor for biomolecular detection in Journal of Physics: Conference Series 34 429

[32] Graak P, Gupta A, Kaur S, Chhabra P, Kumar D and Shetty 2015 A Design and Simulation of Various Shapes of Cantilever for Piezoelectric Power Generator by using Comsol, COMSOL conference, Pune, India.

[33] Bhuyan M S, Majlis B Y, Othman M, Ali S H M, Kalaivani C and Islam S 2013 Development of a Fluid Actuated Piezoelectric Micro Energy Harvester: Finite Element Modeling Simulation and Analysis Asian J. Sci. Res. 6 691-702