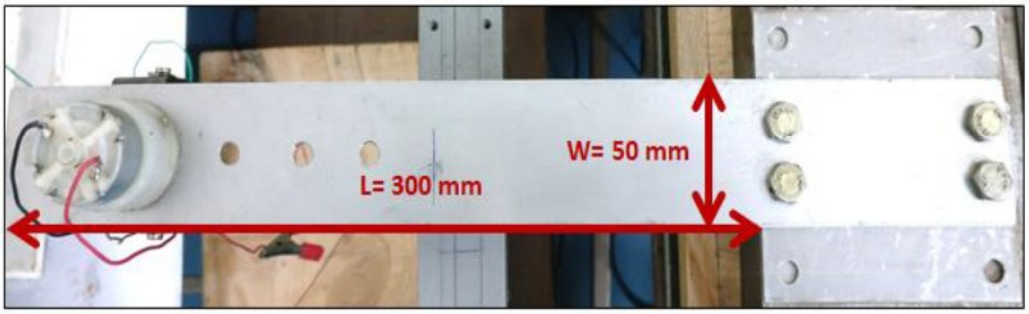
Appendix - I

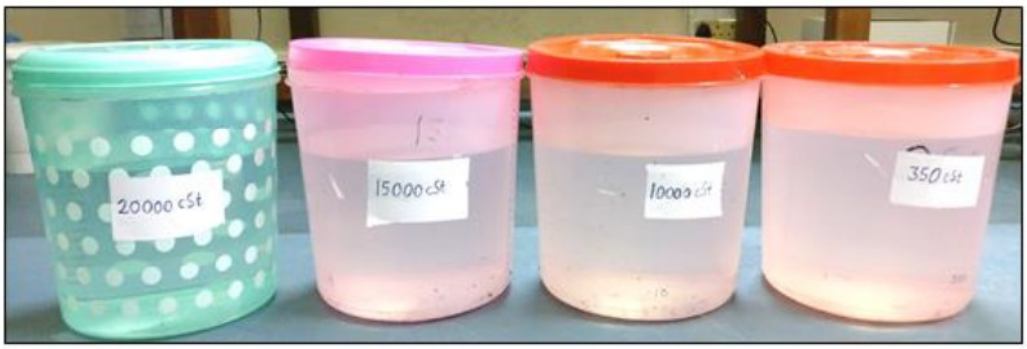
1. Cantilever Beam used as Transducer

The motor flagella assembly is mounted on an aluminium cantilever beam which is 300 mm long. The cross section of beam is rectangular with 50 mm by 1.86 mm.



2. Silicon Oil Containers

Different viscosity of silicon oil is used to maintain the low Reynolds number regime and for performing experiments on various viscosity.



3. PDMS

PDMS is mixed with curing agent in 10:1 to fabricate different designs of flagella.

Appendix - II

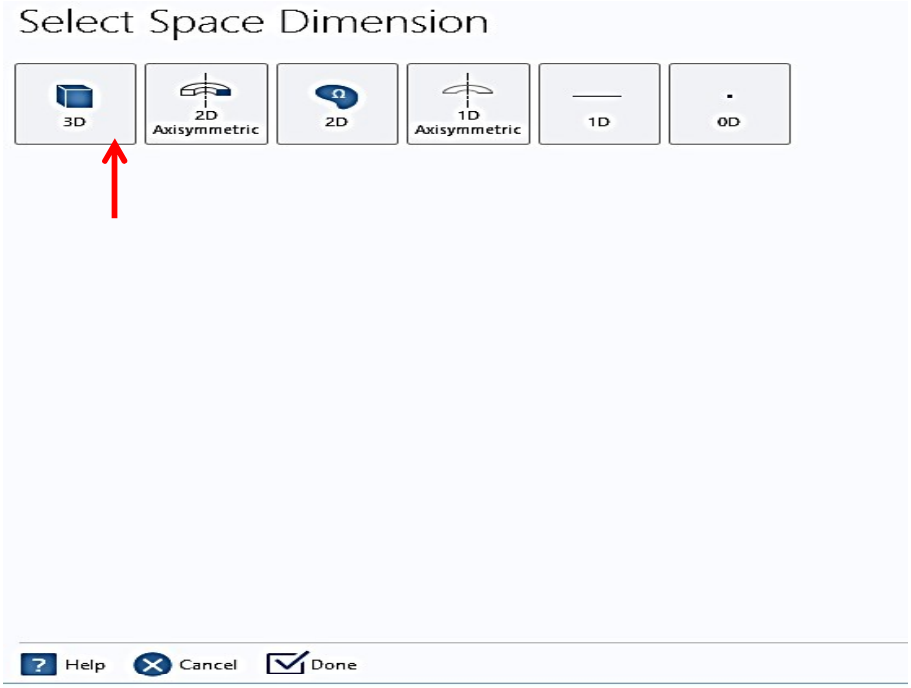
This section details the simulation steps to carry out comparative analysis of stress, electric potential and energy flux generated by different geometries of branched flagella as discussed in Chapter 5. In the section below simulation steps are same for all the simulation studies performed.

The simulation can be divided into following steps:

- ✓ Domain selection
- ✓ Physics and study selection
- ✓ Building of geometry
- ✓ Defining material
- ✓ Applying boundary condition under physics domain
- ✓ Mesh
- ✓ Study

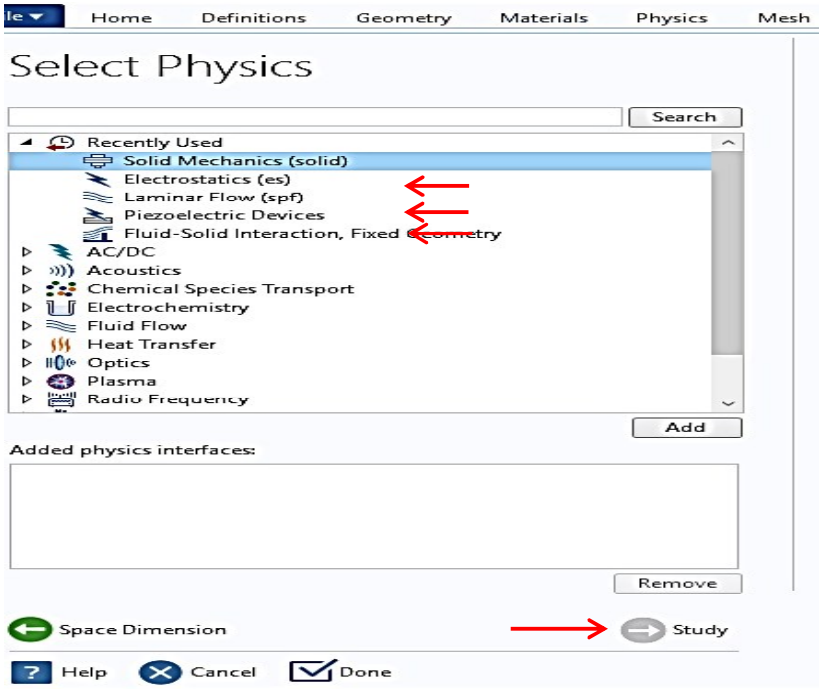
1. Domain selection

First step is to select space dimension. This can be either 0D, 1D, 2D or 3D. In our study 3D domain space dimension is selected.



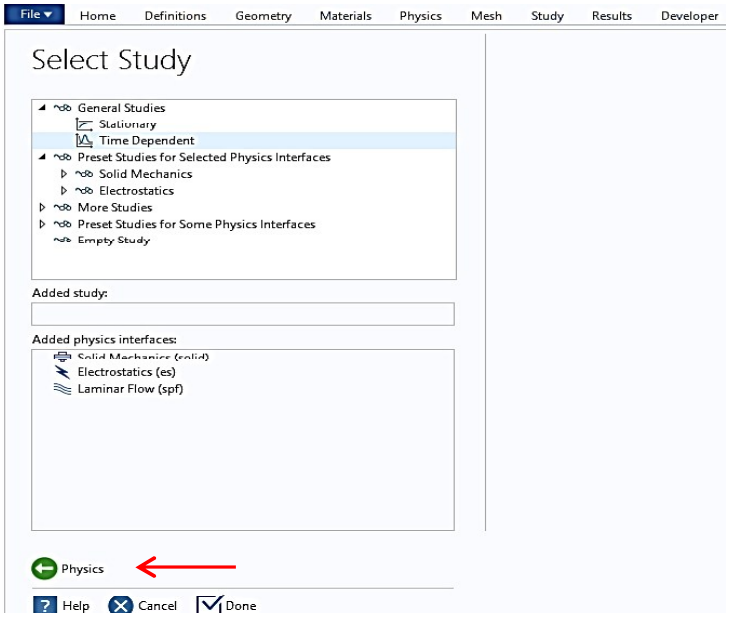
2. Physics selection

After selecting 3D space dimension, it will goes to physics selection domain. Under this step we selected solid mechanics, electrostatic and laminar flow physics. After selecting physics domain go to study selection as mentioned below.



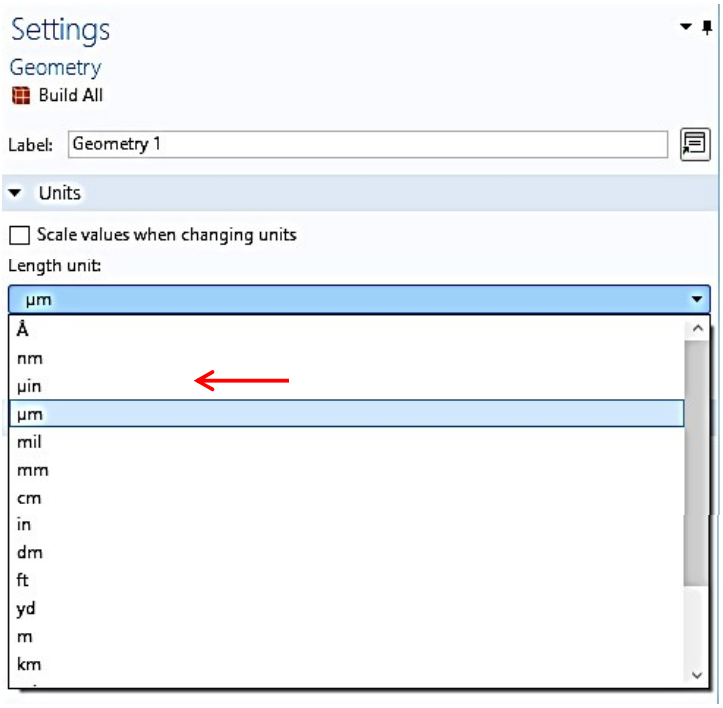
3. Study selection

Under this step, the study which needs to applied is selected followed by pressing done button.



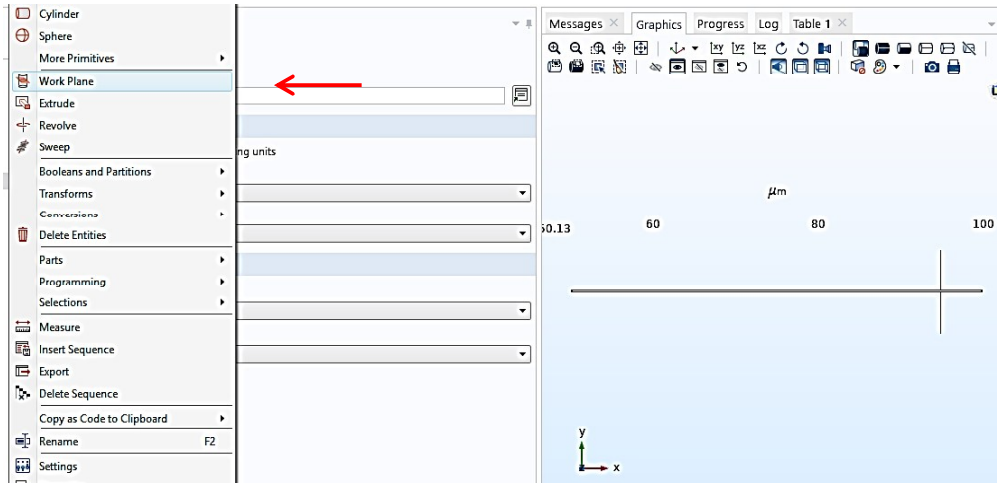
4. Unit selection

Under this step, the unit of the dimension which is to be constructed is selected under the geometry head. Here µm dimension is selected.

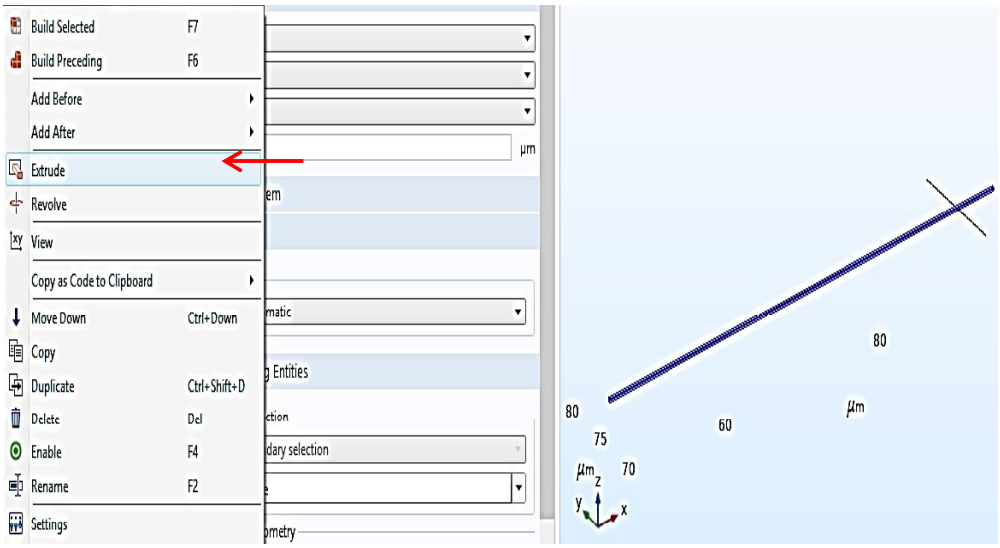


5. Building geometry

For building a 3D geometry, select work plane under geometry head. And under this work plane, click onto plain geometry and select the shape that is to be drawn. In this study, different sets of branched flagella are drawn.

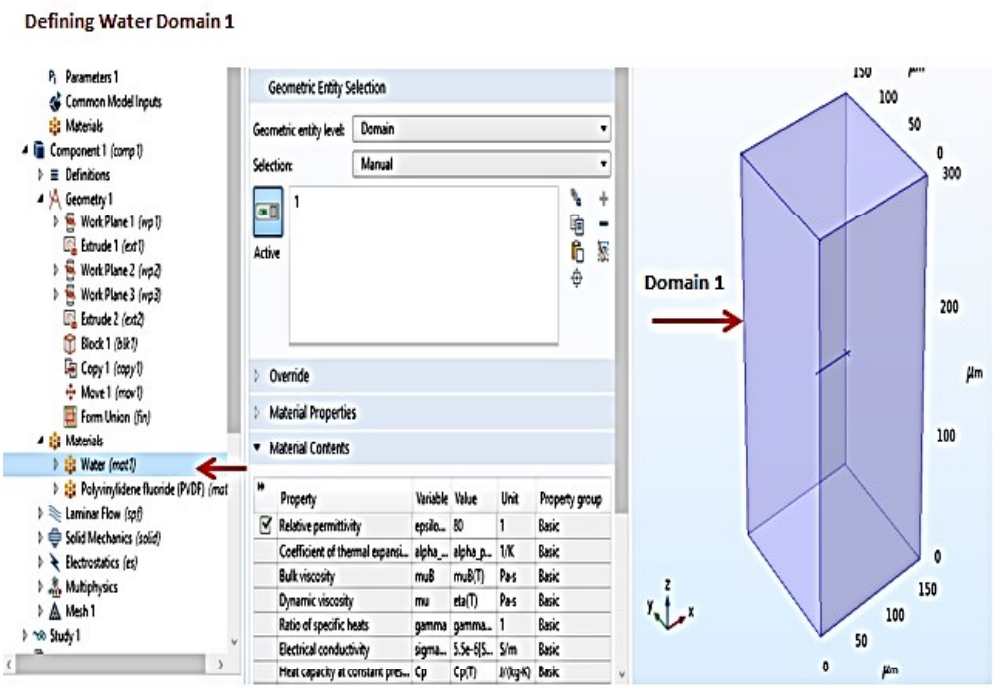


After drawing the geometries, the work plane is extruded to a height so as to obtain 3D branched flagellated structure.

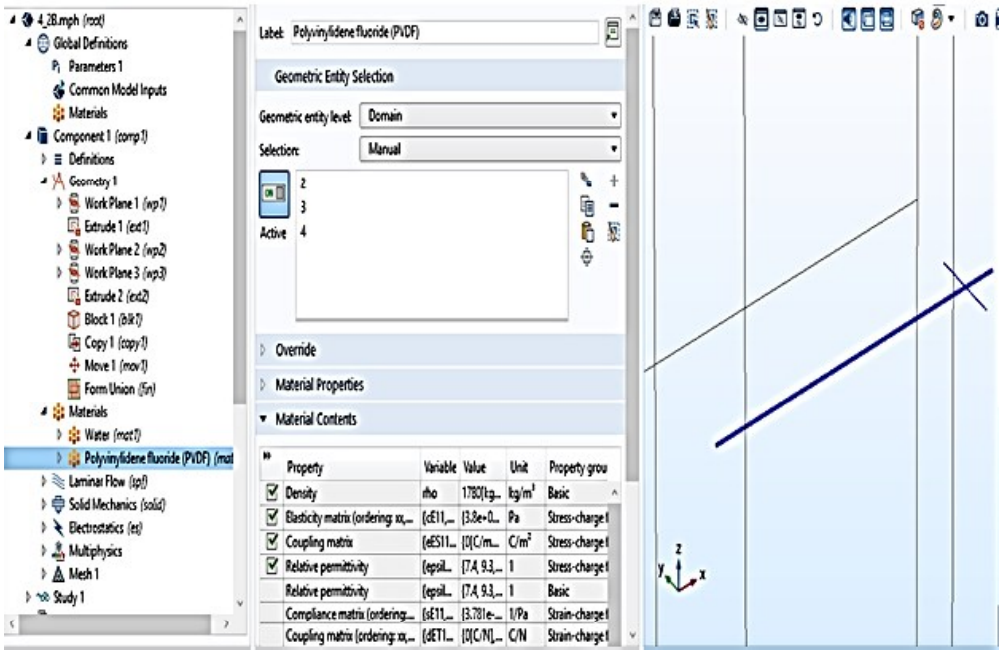


6. Defining material

After drawing the geometry, material is defined to each of the domains. In thissimulation study, Domain 1, the outer domain is selected as water filled tank and domain 2, 3 and 4 is selected as PVDF piezoelectric.

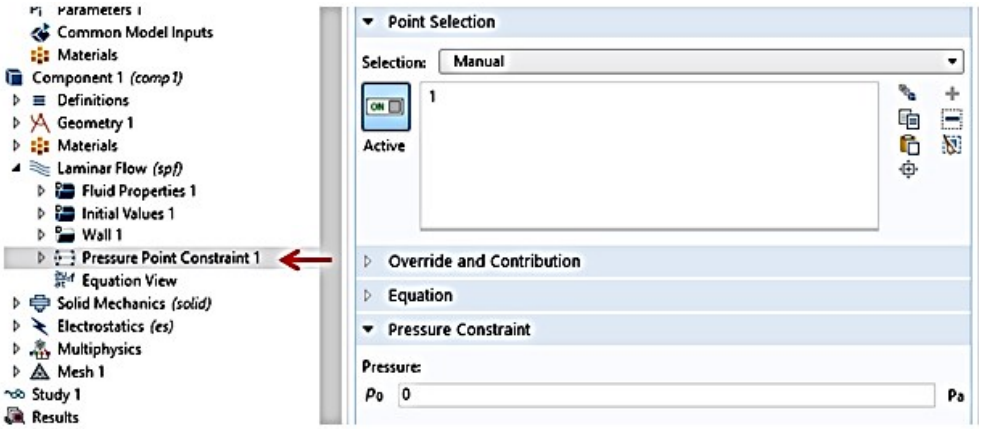


Defining PVDF- Domain 2,3 and 4



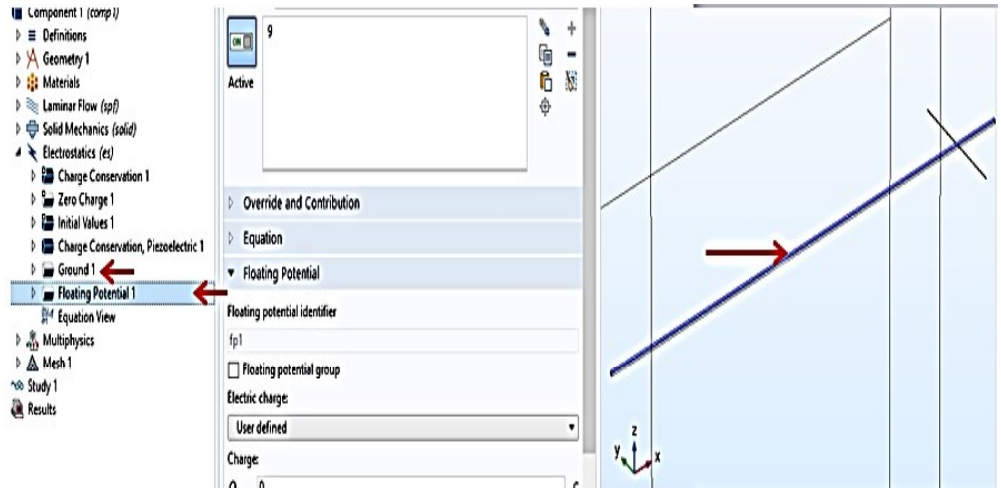
7. Applying boundary condition

After defining the material to the geometry, the boundary conditions are applied. Under laminar flow, any point of outer domain 1 is selected as pressure point constraint to apply 0 pressure.

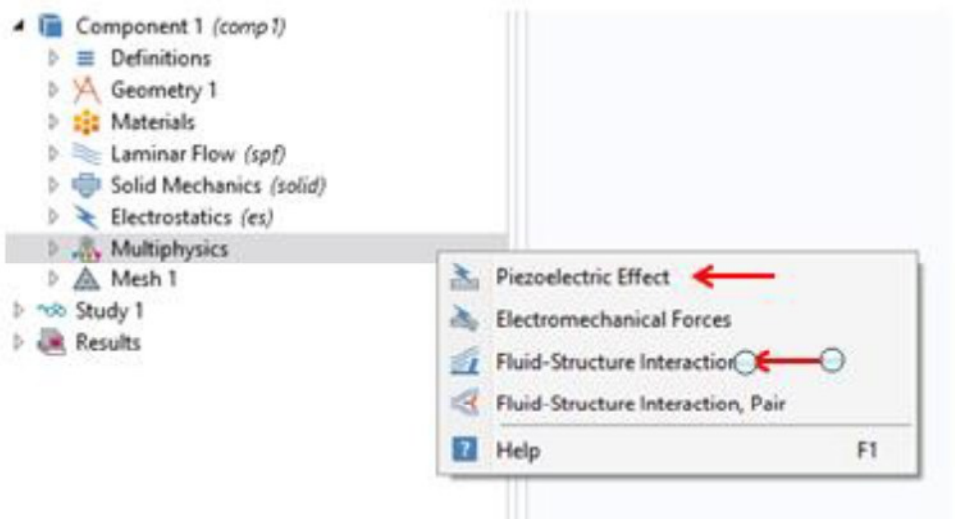


In solid mechanics physics oscillation to one end of branched flagella is provided through prescribed velocity boundary condition.

Under electrostatic physics, ground and floating potential boundary condition is applied to check electric potential generated due to deformation of piezoelectric material.

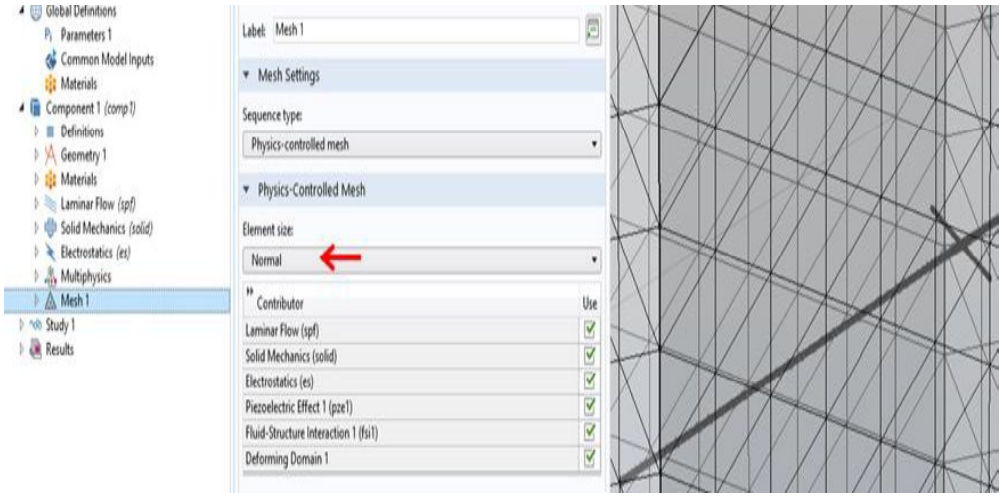


In multiphysics node, laminar flow, solid mechanics and electrostatic physics is coupled together by selecting piezoelectric effect and fluid structure interaction.



8. Meshing

In this step, the geometry is divided into small geometric domains via mesh. Physics controlled mesh along with normal element size is chosen.



9. Computation of study

After carrying out the above listing steps, the model is computed under study node. After software finishes, many results can be obtained in graphic window.

RESEARCH PUBLICATIONS

A. International Journals (Peer reviewed)

1. **Shivani Nain** and N. N. Sharma. "Propulsion of an artificial nanoswimmer: a comprehensive review." *Frontiers in Life Science*, Taylor and Francis, 8, no. 1 (2015): 2-17.
2. **Shivani Nain**, Jitendra Singh Rathore, NN Sharma. "Comparison of Piezo-material based Energy Transduction Systems for Artificial Nanoswimmer". Materials Science and Engineering, vol. 346, no. 1 (2018): 2-9.
3. **Shivani Nain**, Jitendra Singh Rathore and N. N. Sharma. "Experimental Investigation of Biomimetic Propulsion through a Branched Flagellated Nanoswimmer". Australian Journal of Mechanical Engineering, Taylor and Francis, (Accepted).
4. **Shivani Nain**, Jitendra Singh Rathore and N. N. Sharma. "Enhanced Locomotion of Branched Flagellated Nanoswimmer: Design, Simulation and Experimental Investigation". Journal of Mechanical Science and Technology, Springer (under review).

B. Book Chapter

Shivani Nain, JS Rathore, NN Sharma. "Nanoswimmer Energy Transduction System: Influence of Branching. In Engineering Vibration, Communication and Information Processing, pp. 515-522. Springer, Singapore, 2019.

C. International Conferences

1. **Shivani Nain**, Jitendra Singh Rathore and N. N. Sharma. "Effect of Secondary Branching on Piezo based Powering Mechanism to Actuate Artificial Nanoswimmer", ISSS Conference, (4-7 July 2017), IISC Bangalore.
2. Paul Varghese, **Shivani Nain**, JS Rathore, NN Sharma. "Experimental Study on Helical Propulsion System of Artificial Nanoswimmer", IEEE Nano Conference Pittsburgh USA, 25-28 July 2017, The conference proceedings published by IEEE explore, are indexed by EI.
3. **Shivani Nain**, JS Rathore, NN Sharma. "Design to Harness Enough Energy for locomotion of an Artificial Nanoswimmer", ETMN 2017 (6-7 Oct. 2017)), Conference proceedings published by AIP, are indexed by Scopus.
4. Niti Nipun Sharma**, Shivani Nain** and Jitendra Singh Rathore. "Enhanced and self tuned motive forces for locomotion of a nanorobot: Possible solution from nature." American Journal of Advanced Drug Delivery, 7, (2020): 25-26.

Biography of Supervisor

Jitendra Singh Rathore received the B.E. degree in mechanical engineering from Mugneeram Bangur Engineering College, Jodhpur, India, in 2000, the M.Tech. degree in machine design engineering from the Indian Institute of Technology Roorkee, India, in 2005, and Ph.D. degree from Birla Institute of Technology and Science (BITS), Pilani, India in 2014. He is currently an assistant professor at Mechanical Engineering Department, BITS. After working for four years in Industries, He joined the Department of Mechanical Engineering, BITS in 2006 as a faculty member. His research interests include nanorobotics, low Reynolds number, and mechanics of materials.

Biography of Co-Supervisor

Prof. Niti Nipun Sharma completed his B.E. (Mechanical) from REC, Srinagar (now NIT, Srinagar) and M.E. (Mechanical) and Ph.D. both from BITS, Pilani. He is a faculty in Mechanical Engineering Department for over 17 years now currently serving as full Professor in Mechanical Engineering Department. Prof. Sharma served as visiting professor in EPFL, Switzerland during May-August 2014. He is first recipient of Kris Ramachandran best faculty award in 2010 at BITS, Pilani. Prof. Sharma specialized in Robotics and was a part of team which developed 'ACYUT', the humanoid from BITS. He later during his Ph.D. worked on dynamics of nanorobots proposed a simple method to include modelling of Brownian motion attributable to thermal agitation to predict the dynamics of Nanorobots. His methodology of analysing synergism in local and global motion of non-rigid kind of nanoparticles due to thermal agitation from surrounding medium has recently been shown to model radiation of nanoparticle validating with Planck's Radiation Law.

Three patents, over 100 technical papers in high impact factor journals and peer reviewed National and International conferences, around two dozen invited/keynote talks in India and abroad and with ten funded projects from nodal agencies like DBT, UGC, CSIRCEERI, NPMASS and Industries, currently Prof. Sharma is working in Interdisciplinary areas of MEMS and Nanotechnology.

He is Guest Editor, Journal of Bionanoscience (Springer), Associate Editor of International Journal of Smart Sensors and Intelligent Systems, has reviewed many articles for IEEE Tr. Systems, Man and Cybernetics, IEEE Tr. Education, and has been onboard of many Technical Committees of reputed National and International Conference. He was co-chair for Int. Conf. on Emerging Technologies (ETMN-2013), International Conference on Emerging Mechanical Technology Macro to Nano (EMTM2N-2007), co-organized 2nd ISSS-MEMS 2007 conference with CEERI, Pilani and organized Northern Region NPMASS MEMS Software Training Program from 19-24 Feb. 2011.

Prof. Sharma also holds the post of Dean, Academic Registration & Counselling Division at BITS, Pilani since 2010 to 2015. Currently he is Professor and Pro-President at Manipal University Jaipur. He is also Associate Dean at Faculty of Engineering.

Biography of Candidate

Shivani Nain received the B.A.Sc (Bachelor of Applied Sciences) (H) degree in Instrumentation from Shaheed Rajguru College of Applied Sciences for Women, Delhi University, New Delhi, India in 2010, and the M.Sc. degree in Bioelectronics and Instrumentation, Jamia Hamdard University, New Delhi, India in 2012. After completing my M.Sc. degree I joined the Micro Electro Mechanical System (MEMS) Laboratory under Mechanical Engineering Department, Birla Institute of Technology & Science, Pilani Campus, Pilani in August 2012 as a Research Fellow. My research interest includes areas of MEMS, nanorobotics, microfluidic devices, biomedical instrumentation and biosensor.

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