A Review on Advance Piezoelectric Energy Harvesting and their Circuitry System

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Abbreviations and notations:

PVDF	Polyvinylidene Fluoride
MEMS	Micro Electromechanical Systems
PMA-PZT	Lead Methacrylate- Lead Zirconate Titanate
IPMC	Ionic Polymer Metal Composite.
PCGE	Piezo Composite Generating Element
PZT	Lead Zirconate Titanate
PEH	Piezoelectric Energy Harvester
MATLAB	Matrix Laboratory
POF controller	Proportional Output Feedback controller
PID	Proportional Integral Derivative control law
PECBEH	piezoelectric cantilever bimorph energy harvester
FPEDs	flexible piezoelectric devices

ABSTRACT: In this article, significant research projects on waste-energy extraction by using piezoelectric materials are described and discussed with their proposed designs and experimental results. Piezoelectric materials convert mechanical strain energy into electric energy according to piezoelectric effect and vice-versa according to reverse piezoelectric affect. Such materials have been used for sensing and actuating applications at a wide range. This article overviews the different ideas of piezoelectric energy harvesting using hydro dynamism and provides a building block for future research work in the field of utilizing waste fluid vibrational energy.

Keywords: Energy harvesting, piezoelectric effect, piezoelectric materials, hydrodynamics, fluid vibrations, vortex flow.

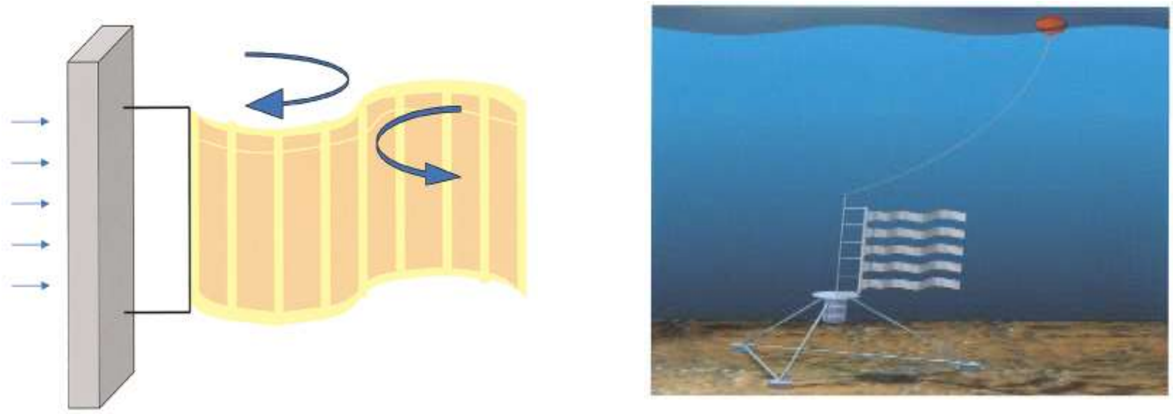
Introduction

Energy harvesting is the operation of extracting energy from the environment, storing and converting it to a usable form. It is an easy way to produce electricity from the energy which is lost or unused. With the advancement in wireless engineering, energy harvesting is highlighted as the alternatives of the conventional battery. Ultralow power portable electronics and wireless sensors use the conventional batteries as their power sources, but due to short and limited life than that of the device their use is somewhere restricted. Consequently, a set of researches have been directed to harvest energy and apply it as a self-power source of portable devices or wireless sensor web system. In the area of energy conversion, human beings have already used energy harvesting technology in the form of windmill, watermill, geothermal and solar energy. These technologies produce kW or MW level power, so generally called macro energy harvesting technology. On the contrast, micro energy harvesting technology is focused on the alternatives of the conventional battery. The micro energy harvesting technology is capable of producing mW or μW level power and is based on mechanical vibration, thermal energy from furnace, heaters and friction sources, room light or sunlight, human body, chemical or biological sources etc.

Piezoelectric materials are capable to produce electric power when stressed. This attribute makes them attractive for energy harvesting from ambient vibrations. The vibration sources can be a machine, human movement, wind, rainfall, tide, waves, etc. The end of power harvesting device is to capture the lost energy from the system and changing it to a usable form for electrical devices to work. With the advancement in wireless technology sensors is being produced which requires a small amount of power to operate. As these are wireless, they involve their own power supplies. An alternative resolution to establish self-powered system is to produce a system which can convert available ambient energy into electrical energy. More or less the ambient energy sources are light energy, mechanical energy, thermal energy, hydro energy etc. We all are surrounded by a great number of machines which produces vibrations. If these vibrations are not cut down, then they may do damage to the machine or to the operator. Usually dampers are used to thin out these vibrations which ultimately results in losing of vibration. Only instead of using damper if we use a piezoelectric material we can easily convert these vibrations into electrical energy which can be practiced anywhere. Therefore, piezoelectric materials have a great number of applications.

Energy harvesting from water is not a new concept. Energy harvesting mechanism for water energy using piezoelectric effect has been started in the 1970s and is still at a developing stage. Much of the research has been done on this concept. Hydropower plant is a best example of harvesting energy from water. But as we all cognize that it can bring about energy at mega level and also requires installation cost and upkeep cost. On the other side the devices with low force or small power need a power source which can offer a continuous supply of power to run. Piezoelectric material can be the best alternative to powering them as batteries has a drawback of limited life span. This article provides different ideas of piezoelectric energy harvesting using water vibrations.

G. W. Taylor (2001) presented a new device called Eel which uses piezoelectric material (PVDF) to convert mechanical strain produced by flow of oceans and rivers into electrical power. Eel generator uses the travelling vortices formed behind a bluff body to strain PVDF. Complete analysis of the Eel model has been done by placing it in a wave tank. These Eels can generate milli watts to many watts depending on system size and flow velocity. Fig.1 shows schematic diagram of Eel and Eel system deployed.

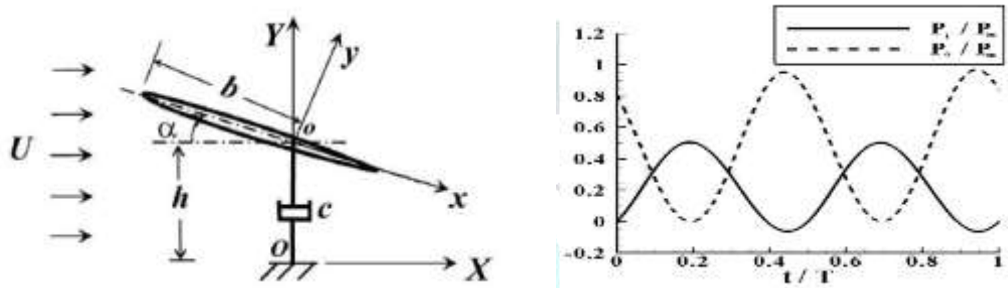


(a) (b)

Fig. 1: (a) Schematic Diagram of Eel (b) Eel System Deployed

Q. Zhu and Z. Peng (2009) examined the performance of device, having flapping foil mounted on damper, at low Reynolds numbers. Navier-Stokes equations have been used to make the numerical model of flapping foil which is further used to analyse the effect of mechanical design and operational parameters. Energy is harvested by creating the pitching motion and using the resulted heaving motion to harvest energy. Difference of energy recovered and energy input is the overall energy recovered. Fig.2 shows an energy harvesting system and variation of input power and output power.

h= heaving motion, α = pitching motion, *a*= chord length, *c* is damper and *U* is incoming flow



(a) (b)

Fig. 2: (a) Schematic Diagram of System (b) Variation of Input Power (P_i) and Output Power (P_o) Over One Period σ = 0.628. α_0 = 15°

L. Tang et al. (2009) presented a model of flutter mill which can be used for energy harvesting from fluid flow. After reaching high flow velocity a cantilever beam is placed in the axial flow becomes unstable and flutter takes place. New device called flutter mill is use to utilize these flutter to harvest energy. Performance of flutter mill was evaluated and power output capacity was compared with a real horizontal axis wind turbine. And it was demonstrated that with compact size flutter-mill, we can achieve high performance. Fig.3 shows the layout, wiring of flutter mill and average power versus flow velocity graph for the system.

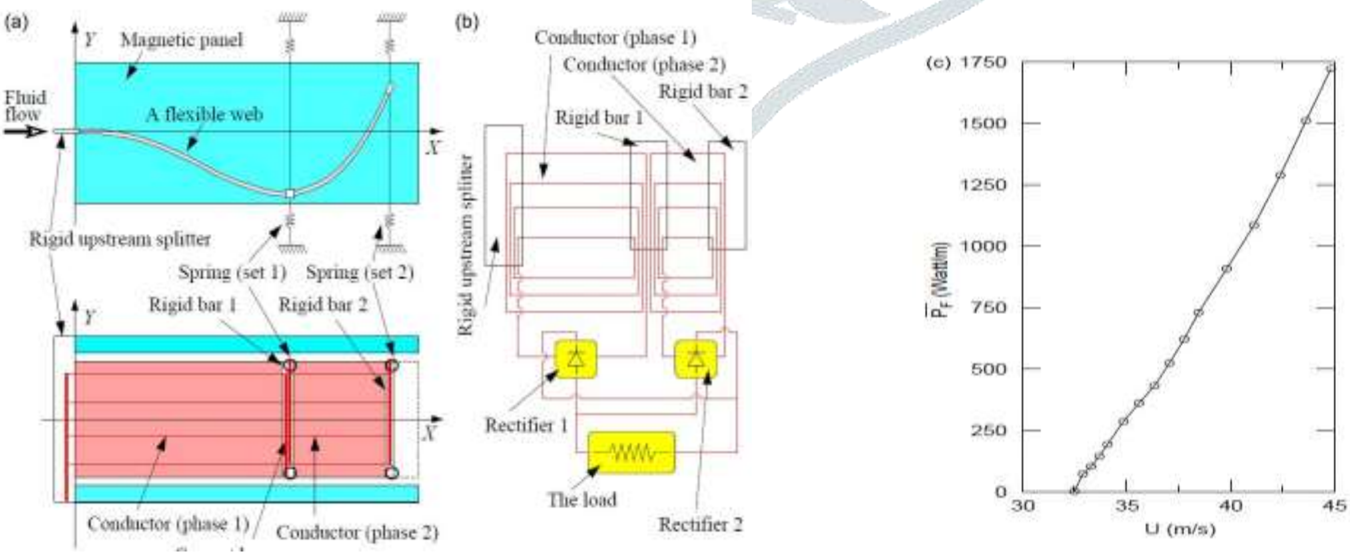


Fig. 3: (a) Layout of Flutter Mill (b) Wiring of Flutter Mill (c) Time Average Power Vs Flow Velocity of Fluid Flow

Y. K. Ramadass et al. (2010) developed a bias-flip rectifier circuit which helps in improving the power extraction from piezoelectric harvesting system by 4 times than conventional full bridge rectifier and voltage doublers. They also proposed a switch only rectifier scheme

where the inductor can't be used. It was found that the power extracted 2 times more than the simple circuit. W. M. Aureli et al. (2010) studied analytically and experimentally the energy harvesting capability of base excited ionic polymer metal composite (IPMC) strip immersed in water and shunted with electric impedance. Surface area and thickness of IPMC were 1.5 cm^2 and 200μm respectively and experiment was carried out in frequency range 2-50 Hz. The maximum power harvested was 1nm for a base excitation of the order of 1mm.
Akaydin et al (2010) presented the analysis of energy harvested from unsteady turbulent flow of fluid using piezoelectric generator. The piezoelectric beams were placed inside turbulent boundary layer and wakes of circular cylinder and the output voltage is recorded. The output voltage depends on location of generator and frequency of fluid flow. Maximum output voltages recorded when frequency of fluid flow is matched with natural frequency of piezoelectric generator. Simulation of the complete system agrees with experimental data. Fig.5 shows the schematic diagram of piezoelectric generator in flow field.

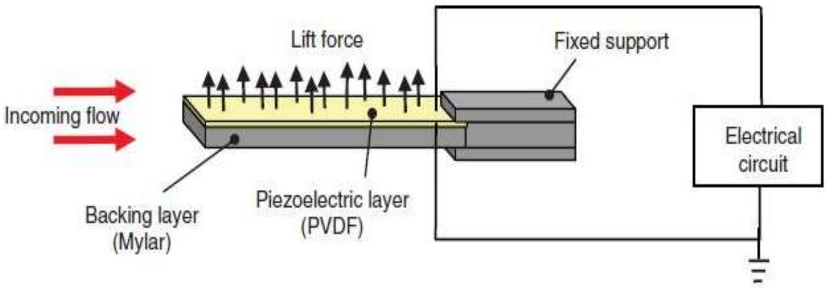
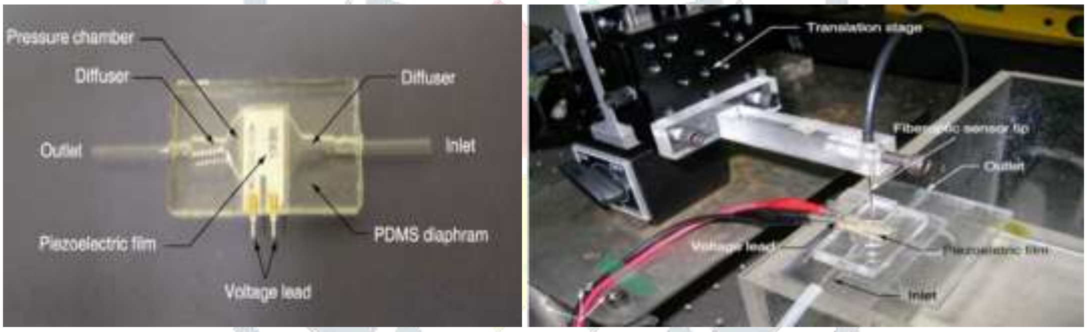


Fig. 5: A schematic diagram of the piezoelectric generator in a flow field

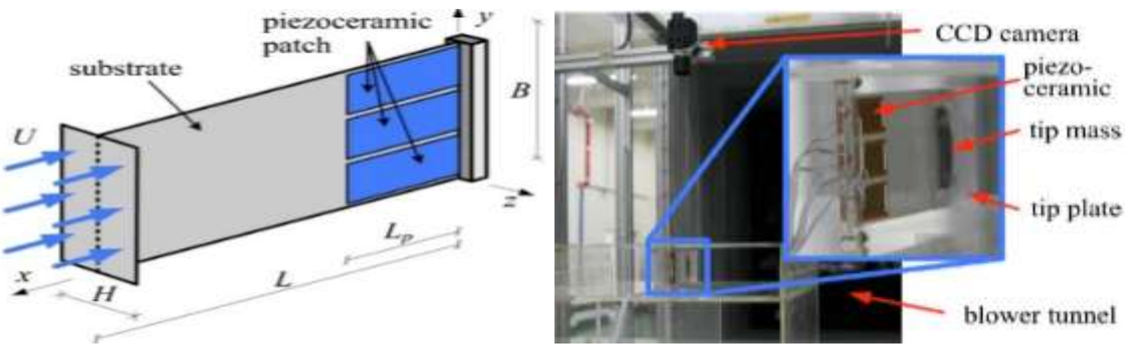
T. M. Kamel et al. (2010) introduced a physical model to predict the power output of MEMS-based piezoelectric harvesting devices. They also designed such model with power output of 140μW. D-A Wang and H-H Ko (2010) developed a new piezoelectric energy harvester by using flow induced vibrations. They also developed a finite element model to estimate the output voltage. When the amplitude of pressure oscillation was 1.196 kPa and frequency was 26Hz then the generated output voltage and power were 2.2V and 0.2μW respectively. Their experimental results agreed well with their finite element analysis. Energy harvester and experimental setup of energy harvester with fluid flow is shown in fig.6.



(a) (b)

Fig. 6: (a) Energy Harvester (b) Experimental Setup of Energy Harvester with Fluid Flow

S. D. Kwon (2010) developed a device consists of T-shaped cantilever to harvest energy. This device works on the principle of aero elastic flutter. T-shape of cantilever increases the occurrence of flutter at low speed of fluid. This device can produce power from wind at minimum speed of 4m/s and maximum power is 4.0mW. This device is extremely cost effective because it consists of only a bimorph cantilever. Schematic diagram and experimental setup of device is shown in fig.7.



.Fig. 7: Schematic diagram and experimental setup of device

R. Patel et al. (2011) showed the effect of geometric parameters on the performance of a piezoelectric cantilever micro scale energy harvester which is undergoing harmonic base excitation. They showed that on reducing piezoelectric layer length there is significant increase in energy storage. Xuan-Dien Do et al. (2011) proposed a new high efficiency piezoelectric energy harvester by using two synchronized switches and conventional full bridge rectifier was replaced by active diode to increase the conversion efficiency of rectifier. They showed that the power extraction efficiency was 3.5 times than the conventional rectifier under same load conditions. A low drop regulator was used which gets

maximum 90% efficiency with 3mW voltage ripple and the overall efficiency of system was 83.3%. Lee and Youn (2011) proposed a new multimodal energy harvesting skin which was obtained by removing the PZT material from multiple modal shapes along the inflection line. On comparing with unimodal energy harvesting skin and skin without segmentation, they showed that multimodal skin was superior in energy production by study of two cases- for an aircraft skin vibration and a power transformer vibration. Heung Soo Kim et al. (2011) reviewed energy harvesting technology from mechanical vibrations along with various types of vibrations devices, piezoelectric materials and mathematical modelling of Vibrational energy harvestings. To improve the performance of PEH, result of their study includes following issues: (1) High coupling co-efficient piezoelectric material (2) Development of flexible piezoelectric materials. (3) Development of efficient electronic circuitry. A. Khalatkar et al. (2011) investigated the optimal placement of piezoelectric actuators in a cantilever beam for maximum energy harvesting. They observed that for maximum energy harvesting, width of piezo-patch should be maximum, length of patch should be nearly half of beam length and patch should be placed at the middle of the beam. Erik Malino-Minero-Re et al. (2011) presented a model of energy harvesting system for scavenging energy from water. This system can harvest energy from induced water vortexes using piezoelectric materials and small cylinders. Results showed that some of the configurations can generate a power of up to 0.31mW.
Chhabra et al. (2012) revealed that linear quadratic regulator scheme was very effective in controlling the vibrations. From the various locations of sensor on beam, it was observed that when piezoelectric element is placed near the fixed end then the best performance of control was obtained. Fig.8 shows the schematic configuration of system and displacement graph without and with pole placement method.

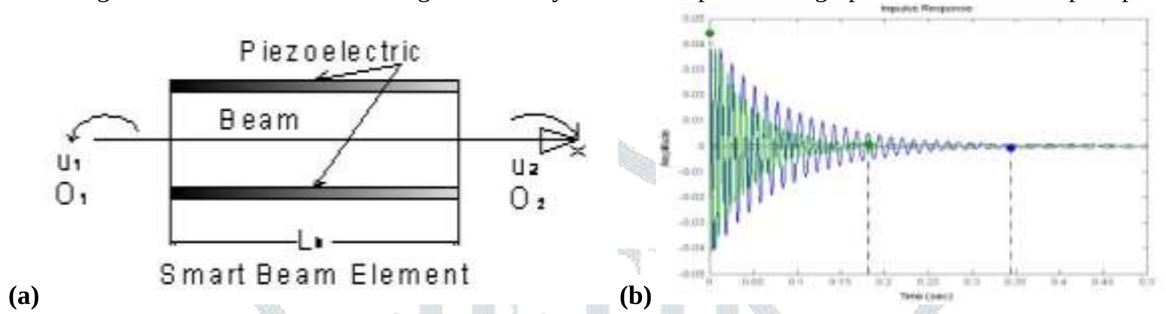


Fig. 8: (a) Schematic Configuration of System (b) Tip Displacement without and with Pole Placement Method

N. L. Kim et al. (2013) proposed honeycomb shaped piezoelectric energy harvester. Output characteristics of device were defined through finite element analysis and on the basis of these results such harvesters were fabricated and experimented. They proved that higher output voltages were obtained from longer length ceramics. M S Bhuyan et al. (2013) presented a piezoelectric fluid flow based micro energy harvester based on a piezoelectric cantilever affixed to a bluff-body. They designed and modelled a MEMS-based energy harvester structure. In a cross fluid flow, pressure in the flow channel fluctuates and this fluctuation in pressure causes the piezoelectric cantilever to vibrate in a direction normal to the fluid flow direction. To evaluate various mechanical analysis of the micro energy harvester, COSMOL finite element analysis software is used. Their modelling and simulation results were comparable. G. A. Athanassoulis and K.I. Mamis (2013) modelled a hydro/piezo/electric system. They installed a piezoelectric material sheet on a vertical cliff placed in sea waves and connected to an external electric circuit on land. Here the hydrodynamic pressure of sea waves is used for excitation purpose. They found that their project can become 30-50% significant depending on piezo, hydro and electric parameters and can produce useful energy. D. J. Shin et al. (2014) fabricated the multilayer ceramic-pillar composite structures for piezoelectric energy harvesters and analyzed it with increase in number of layers from single to triple layers. The generated maximum output voltage and maximum output power were 10.2V and 14pW respectively for the triple layers. H. Huang (2014) investigated the piezoelectric cantilever bimorph energy harvester (PECBEH) under the various proof masses and electric load resistant. When the electric load resistant approaches to matching impedance of the PECBEH then maximum damping ratio was obtained. Chhabra et al. (2014) worked on controlling the active vibrations of beam like structure with distributed piezoelectric actuators and sensor layers bonded on top and bottom surfaces of the shaft. The location of piezo-patch was examined on fixed, middle and free ends. The study included simulation in MATLAB for controller such as POF, PID and Pole displacement technique. X.D. Xie et al (2014) developed a model to harvest sea wave energy by converting kinetic energy of sea water into useable electric energy. A cantilever beam attached with piezoelectric patches and point mass is used for collecting energy. Practical observation and mathematical simulation shows that generated power increases with width to thickness ratio of cantilever, ratio of point mass with cantilever mass, sea depth, wave height. Generated power from the model is 55 W and simulation shows that 145 W can be achieved with l=6m, b=3m, h=0.12m with sea wave height=3m. Fig.9 shows the schematic diagram of piezoelectric energy harvesting system and model subjected to sea pressure.

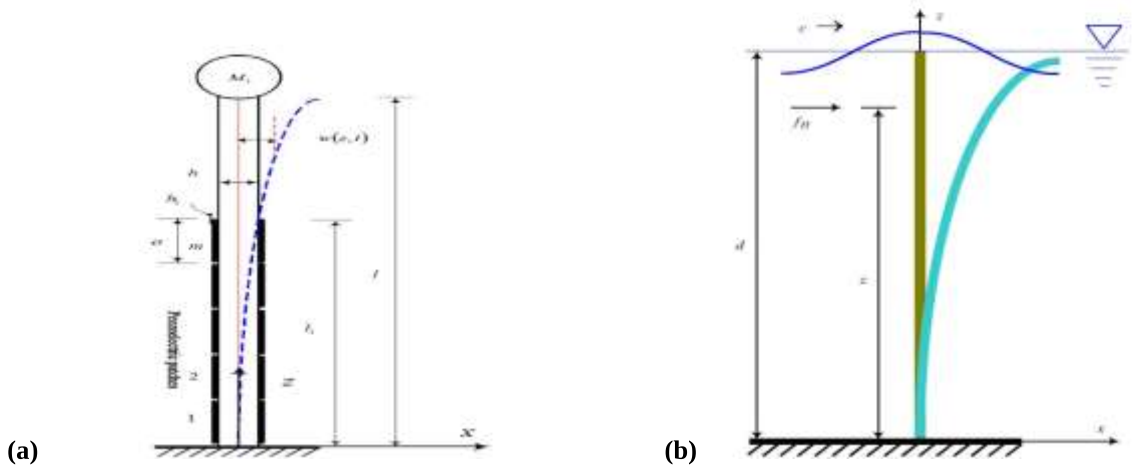
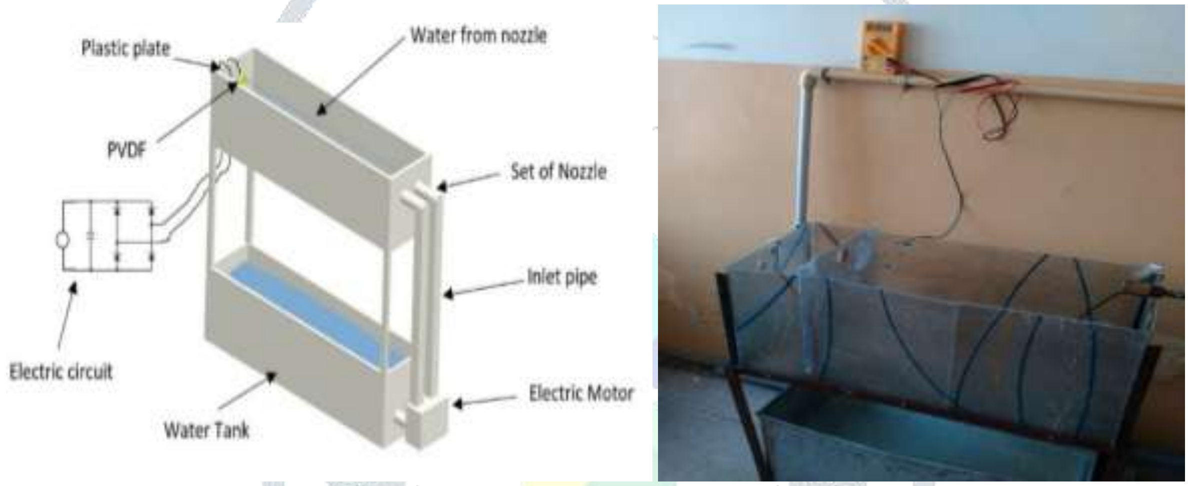


Fig. 9: (a) Setup of Piezoelectric Energy Harvester (b) Model Subjected to Sea Pressure

V. Bhatnagar and P. Owende (2015) reviewed the energy harvesting techniques, power conversion and characterized self sustaining power generation systems in 600μW to 5W range. M. Guan et al. (2015) designed a frequency tunable piezoelectric energy harvester, simulated and verified it experimentally. The d_{33} coupling mode had a better resonant frequency variation ratio of 28.59% as compared to d_{31} mode which has 4.42% highest frequency variation ratio. Koyvanich et al. (2015) proposed an energy harvester that converts fluid flow energy into electrical energy by using a flexible piezo-film and a vortex induced vibration technique. An open circuit voltage of 6.6 mW at a matching load of 1MΩ was generated with maximum output power of 0.18μW. Efficiency power conversion of the proposed energy harvester was 4.4%. Y. Tanaka et al. (2015) performed an experiment using flexible piezoelectric devices (FPEDs) and generated power from wave energy in two alternate configurations. In one configuration FPEDs are perpendicular to seabed and in the second these are parallel to the seabed. They made the harvesters to excite in the wave and base was fixed. They also developed a theoretical model to evaluate the force created by the wave. Their experimental and theoretical results agreed well for different wave heights and water depths.
P. Rani and D. Chhabra (2016) presented a model for energy harvesting by using dynamic pressure of water on a single patch of PVDF with two different circuits- voltage doubler and full bridge rectifier circuits. Voltage doubler circuit provided maximum voltage of 17.54V and full bridge rectifier circuit provided 7.01V maximum voltage at 75cm from nozzle end. A. Budhwar and D. Chhabra (2016) developed a model for energy harvesting using PVDF piezoelectric material with hydrodynamism. A dynamic water pressure has been directed on PVDF patches and a comparision has been made for output generated output on the basis of different nozzle angles, distance of nozzle from patches, number of patches and different electronic circuitry. It was found that when double patches are connected in series then there is maximum generated output voltage. Jyoti Yadav and Dinesh (2016) proposed a mechanical model which was composed of a water tank, a set of nozzle to increase the velocity of fluid, pipe to circulate the water flow, PVDF patches mounted on a plate and voltage doubler circuit to generate output terminal voltage of the order of approximately 17 Volts. The model can be used where the water supply is continuous such as river, lakes, bridges, waterfall, etc. In case, if water is present in limited quantity then a reservoir tank can be used to store the water and a pump can be used for recirculation of the water. Schematic diagram and proposed model of apparatus is shown in fig.10.



(a) **(b)**
Fig. 10: (a) Schematic Diagram, (b) Experimental model of Apparatus

Conclusions
Small scale mechanical energy harvesting has been studied using piezoelectric materials with hydro-dynamism. An overview has been given about different aspects of energy harvesting using fluid flow generated vibrations. Also some research projects has been mentioned here regarding significant energy harvesting using interaction of piezoelectric materials and flowing fluids. Nevertheless, waste mechanical energy harvesting will be one of the most important energy technologies in the near future.

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