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Research Article

Sensitivity analysis for piezoelectric energy harvester and bluff body design toward underwater pipeline monitoring

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Abstract: Monitoring of underwater pipelines through wireless sensor nodes (WSNs) is an important area of research especially for locations such as underground or underwater pipelines, where it is costly to replace batteries. In this study, a finite element sensitivity and comparative analysis for piezoelectric (PZT) energy harvester operating in a fluid flow is done to power underwater in-pipe WSNs. Two types of bluff bodies D and I-shaped are used for comparison. Finite element simulations results show that PZT energy harvester having I-shaped bluff body produces 2.24 mW, while energy harvester having D-shaped bluff body has the capacity to produce only 0.82 mW of power. I-shaped bluff body have significant impact on the performance of pipe and it introduces 6 times more head loss than D-shaped bluff body to maintain regular flow of pipe for the same fluid domain. It is concluded from the analysis that 12 PZT cantilevers in parallel arrangement are needed to maintain 4096 bits per second (bps) transmission of 512-Byte data packet once per 5 minutes with the piezoelectric harvester, using an integrated 7.1 J super capacitor that can fit into the bluff body together with the power electronics and acoustic transceiver.

Keywords: *Wireless sensor nodes; bluff body; piezoelectric energy harvester; underwater pipelines; performance impact*

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Nomenclature	
ρ	Density of fluid
η	Dynamic viscosity of fluid
ε_0	Absolute permittivity of material
ε_r	Relative permittivity of material
B	Width of piezoelectric cantilever
D	Dimension of bluff body
f	Frequency of beam
g	Acceleration due to gravity
d_{31}	Dielectric constant
E	Young modulus of material
L	Length of piezoelectric energy harvester cantilever
p	Pressure across the surface of cantilever
P_{el}	Electrical power
R_e	Reynolds number of bluff body
T	Thickness of piezoelectric cantilever
v	Velocity of fluid
W_{el}	Electrical Energy

1. INTRODUCTION

Energy harvesting is an attractive field of research in sustainable technology applications where operational energy needs to be extracted from the surrounding sources due to lack of connection with grid or battery. One of the most prominent applications of energy harvesters is providing electrical power to drive wireless sensor nodes (WSNs) in locations with limited accessibility such as underwater or underground pipelines [1].
International Energy Agency (IEA) has also recognized the importance of sustainable energy technologies and emphasized on the fact that nations should collaborate on programs such as International Energy Agency's (IEA) Hydrogen Program to promote these types of technologies [2]. Technologies such as renewable energy and energy harvesting have the ability to provide energy with sustainability to the vast populations but at the same time, their social, economic and environmental impact should be also taken into consideration during their deployment [3]. In order to achieve the objective of sustainable and clean energy, ecological and technical (eco-tech) built environment is equally important which converts the negative impacts of technology into positive by using natural sources of energy while following the rules of sustainable development [4]. That is why; this study presents performance impact on the pipe in terms of head loss due to deployment of PZT energy harvester into the pipeline.
Previous publications in this area have not sufficiently discussed comparative analysis between different types of bluff bodies attached to PZT energy harvesters for the requirements of different applications. The impact of PZT harvester having different types of bluff bodies on the performance of a fluid delivery pipe has also been ignored in previous studies. This paper addresses these holes in the literature, in addition to delivering finite element models and simulations to verify and quantify the sensitivity of the energy harvester performance to the fundamental design parameters.
Fig. 1. presents the block diagram of WSNs where all components and subsystems are enabled by the power generation unit [12]. It is essential for the power unit to meet the power requirements of all subsystems including sensing, communication and computing for the successful operation of WSNs. For underwater pipelines, radio frequency communication is not feasible due to security reasons and non-availability of air underwater, so acoustic communication is a viable alternative. However, acoustic communication has high power requirement ranging from 1.224 W to 102 W depending upon the network architecture and distance between nodes [13]. Due to this reason, deploying the energy harvesters to meet the minimum power requirements is a challenging task. This study investigates this aspect of research, which is an important literature gap, and seeks minimum dimensions for bluff body and PZT cantilever system to extract sufficient power from the fluid flow to meet the energy requirements of WSNs. In addition, the designed energy harvester successfully generates “von Kármán's vortex street” for the fluid flow conditions specifically for the Turkey-Cyprus water pipeline project considered as a case study. An implementation based on PZT energy harvesting from water flow is used to operate WSNs, with minimum quantified impact to the native flow rate and/or water pressure.

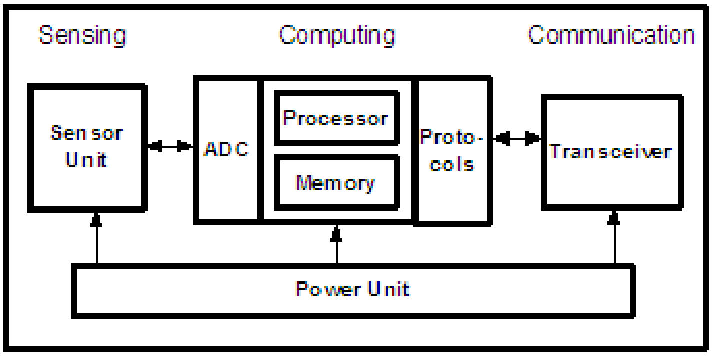


Figure 1. Wireless sensor node block diagram [12].

The rest of the study is organized as follows: In Section 2, energy requirements of WSNs and in-pipe energy harvesting technologies with potential to provide this power in underwater pipeline application are comprehensively investigated. Analytical calculations, simulation methodology, geometric modeling and boundary conditions are performed for the selected PZT energy harvester in Section 3 to determine the rough dimensions of the required structure. Comparative analysis between I-shaped and D-shaped bluff body and its finite element results have been investigated in section 4. Section 5 presents the detailed sensitivity analysis using finite element method, including complete geometric modeling for the accurate design of the energy harvester. Section 6 concludes the study and outlines future work.

2. BACKGROUND

Wireless sensor network consists of WSNs for their operation and these nodes need electrical power to operate. Batteries are usually used to produce electrical power for WSNs [5]. Sometimes, it becomes very difficult to install battery in places, which are difficult to locate due to need of regular replacement and high cost of maintenance [6]. Therefore, using energy harvesting as a source for producing power for WSNs is an attractive option since there is no need of power supply and maintenance but producing enough power for the operation of WSNs is a big challenge while using this choice [7]. Wind, Solar and Thermoelectric are the most commonly used types of energy harvesting [8], [9]. These sources of energy are not reachable in underwater pipelines so other options available for energy harvesting are electromagnetic and piezoelectric (PZT) energy harvesting [10]. Performance impact due to the substantial size of the micro-turbines, and their maintenance requirement make electromagnetic harvesters undesirable for underwater pipelines [11]. That is why, sensitivity analysis for piezoelectric energy harvester and bluff body design toward underwater pipeline monitoring is investigated in this study.

2.1. In-pipe Energy Harvesters

Numerous energy harvesting techniques have been discussed in the literature to produce electrical energy but PZT energy harvesting is the most attractive due to minimal maintenance requirements [11]. PZT energy harvesting from fluid-flow induced vibration is presented in [14], where the kinetic energy from water flow is transformed into electrical energy by using PZT cantilevers. Fluid flow exerts pressure impulse on PZT cantilever beam due to vortex shedding which produces fluctuation of cantilever in the direction perpendicular to fluid flow. In addition to lacking the important consideration of comparative analysis between different types of bluff bodies for PZT energy harvesting these studies did not provide sufficient details of a performance impact on the pipeline. This study primary focuses on these aspects of PZT energy harvesting. This study also presents the geometry optimization by using sensitivity analysis in finite element software, which is an important hole in the literature.

2.2. Power and Energy Requirements of In-Pipe Wireless Sensor Nodes

Jinhao et al. [15] compared four different types of power electronics circuits for the vibration based PZT energy harvesters. According to this study, synchronized switching technique brings major enhancement in terms of efficiency to vibration-based PZT harvesting systems. Different power electronics conversion circuits are investigated in the literature which are compared in Table 1 with respect to their features and performance evaluation[15,16]. This table shows that energy harvester voltage doubler, and buck boost sensor less energy harvester circuits have high efficiency, with requirement of single supply voltage. Both of these power conversion circuits are compatible with micro-scale integration. However, buck boost energy harvester circuit has highest efficiency of 84% among all circuits but it is not able to adjust with rectified voltage. On the other hand, voltage doubler energy harvester circuit has lower efficiency of 60%, but able to synchronize with rectified voltage. Hence, power conversion mechanism is selected based on power and voltage output requirements.

In order to estimate the power requirements of WSNs, a literature review is conducted. MSP430F1611 16-bit microcontroller has been chosen after thorough research for the system power estimation due to low power requirement of 4.36 mW with many combined peripheral options and relatively large on-chip flash and SRAM memory types [17]. The power requirement of the acoustic transceiver is estimated at 1.75 W corresponding to Linkquest Company UWM 100 Transceiver with a range of 0.35 m [13]. A sensor subsystem with 15 mW power dissipation is considered for underwater pipeline monitoring, including pressure, temperature and Ph sensing [5].

Table 1. Comparison of different types of PZT harvester power electronics circuits

Power conversion method	Features
Standard full bridge rectifier	Very low efficiency circuit, which is not able to adjust rectified voltage to extract maximum power so non-adaptive. No external supply is required and compatible with micro scale integration.
Voltage doubler	Low Efficiency with non-adaptive problem. Implemented as Complementary Metal-Oxide Chip
Optimized energy harvester for full bridge rectifier using step down converter	Multi-supply voltage required for operation with efficiency fairly high.
Adaptive energy harvester for full bridge rectifier using step down converter	Need multi-supply voltage but the circuit is adaptive. Efficiency and losses are not discussed in the study
Buck boost sensor less energy harvester	Sensor less and non-adaptive. Efficiency above 84% for given piezoelectric parameters. Also compatible with micro scale integration.
Synchronized switch harvesting	Circuit is non adaptive but the efficiency is 70%
Adaptive energy harvester using voltage doubler	Efficiency of 60% and the circuit is adaptive with single supply voltage. The circuit is also compatible with micro scale integration

The processing and transmission power requirement of a wireless sensor node does not have to be promptly met by the energy harvester, since the node is not anticipated to be constantly active. The idle time between data capture and transmissions depends on the WSN system design and associated algorithms, and may differ between many milli-seconds to minutes. Similarly, the total transmission time is governed by the number of data packets transferred, and may not last more than tens or hundreds of micro-seconds (μs). Therefore, while the power electronics design in the node has to target active power dissipation constraints, energy requirements are more relevant to the design of the energy harvester. The data packet size can be taken as 512 bytes since it is enough to meet the requirements of WSN with a data transmission and receiving rate of 4800 bits per second (bps) [18]. It means that data transmission or receiving time is 0.85 sec for the active power dissipation of the representative 2.02 W which means an energy requirement of 1.72 J. Suppose that WSNs has an active power dissipation requirement every 5 minutes. An energy harvester constantly generating 0.492 mW will have generated 147.6 mJ in five minutes, considering 60% power conversion efficiency between generation and application. It means that there is a requirement of 12 PZT energy harvesters connected in parallel to a single bluff body to meet the energy requirements of WSN.

Energy storage device is needed for an energy harvester continuously generating energy. Traditional electrolytic capacitors, super capacitors and rechargeable batteries can be used as energy storage option for PZT energy harvester. Electrolytic capacitor is not an attractive option to be used as an energy storage device for PZT energy harvester since it has low energy density [19]. Table 2 illustrates some standard energy capacities of super capacitors and rechargeable batteries. It can be seen from the table that rechargeable batteries have much more higher density than super capacitor but still super capacitor having discharging voltage from 4V to 2V can easily meet the requirement of WSN.

Table 2. Different types of energy storage devices [19].

Energy storage device	Charge capacity	Unit	Energy capacity (J)
Capacitor	0.47	F	7.1
NiMH Battery	110	mAh	475.2
Lithium Battery	190	mAh	2462.4

3. ANALYTICAL MODEL, GEOMETRY MODELLING AND BOUNDARY CONDITIONS

PZT cantilevers should show continuous vibration for successful generation of electrical power. Energy of fluid flow produce bending forces on the cantilever, which then produce a pattern, called “von Kármán's vortex street” which assures repetitive oscillations of PZT cantilevers. Fig. 2 presents the schematic diagram of working principle of PZT energy harvester where the flow passes over the bluff body and produces a pattern of sporadic vortices at each side of the bluff body and due to this continuous kinetic energy of fluid cantilever starts to vibrate in both clockwise and anticlockwise direction in a periodic manner.

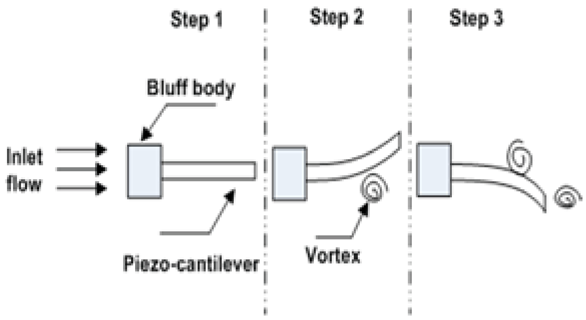


Figure 2. Wireless sensor node block diagram [12]

The Reynolds number should be between 50 and 10,000 for the necessary production of "von Kármán's vortex street" [11]. The dimension of bluff mainly depends upon Reynolds number as represented in Eq. (1) .In this study, our main purpose is to get maximum power. Maximum dimension was found for this purpose since it is directly interrelated with the length of energy harvester [20] .Since, it is compulsory for the energy harvester to vibrate in the first harmonic mode so it should follow a certain ratio as explained in [21] and this is presented in Eq.(2). Where v, ρ, η, Re, L, and D donates the velocity, density and dynamic viscosity of fluid, Reynolds number of bluff body, length of energy harvester and Dimension of bluff body.

$$D = \frac{\mathrm{Re}.\eta}{v\ .\rho} \tag{1}$$

$$\frac{L}{D} = 2.215 \tag{2}$$

The thickness of the beam is taken according to ratio defined in [22] and [23]. The pressure p across the surface of energy harvester can be shown by a simple relation of Bernoulli Equation where the rotational velocity is assumed to be one third of flow velocity as shown in Eq. (3) [21].

$$p = \frac{\rho}{2}((v\ - \frac{v}{3})^2 - v^2)) \tag{3}$$

The frequency f_{beam} of the beam and electrical energy are important parameters because useful electrical power depends upon them. Their relation is presented in Eq. (4) and Eq. (5) respectively. E, T, B, d_{31} , ε_0 and ε_r represents young modulus of material , thickness and width of PZT cantilever, dielectric constant, absolute and relative permittivity of material [24],[13].

$$f_{beam} = \frac{1}{2\pi}\sqrt{\frac{35}{33}(\frac{ET^2}{L^4\rho})} \tag{4}$$

$$W_{el} = \frac{1}{128}.p^2.\frac{d_{31}}{\varepsilon_0.\varepsilon_r}.\frac{B.L^5}{T^3} \tag{5}$$

The electrical power relation is shown in Eq. (6) which depends upon frequency of beam and electrical energy output [21].

$$P_{el} = 8.f_{beam}.W_{el} \tag{6}$$

The bluff body produces flow disorder and supports the cantilever, and is thus one of the most essential components of the piezoelectric energy harvester placed in fluid flow. It interrupts the normal fluid flow and generates flow disturbing bodies, named "von Karman's" vortex street. Fig. 3 depicts the illustration of a piezoelectric energy harvester supported by D shaped bluff body operating in a fluid flow.

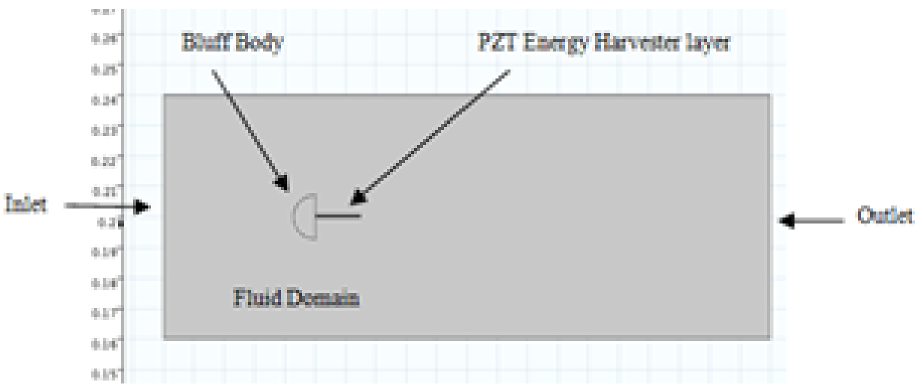


Figure 3. Schematic diagram of finite element model

The generated von Karman's street can be observed in the figure, which ensures continuous vibration of the energy harvester when fluid exerts pressure on the bluff body due its kinetic energy. As a result, bimorph piezoelectric vibration energy is used to convert the energy in to the electricity. Based on the specifications of the selected Turkey-Cyprus water pipeline as the case study, 1.4 m/s with turbulent flow conditions is applied at the inlet and pressure of zero is provided at the outlet. Table 3 presents geometric properties of PZT energy harvester used in the finite element analysis.

Table 3. Geometric properties of fluid and energy harvester.

Modeled Parts	Geometric Property	Numerical Value	Unit
Fluid Channel	Length	200	mm
	Height	80	mm
Solid Cantilever	Length	15	mm
	Thickness	0.35	mm
PZT Layer	Length	15	mm
	Thickness	0.35	mm
D-shaped Bluff Body	Diameter	7.14	mm
I-shaped bluff body	Height	7.14	mm

Cantilever used in the Energy harvester is made of plastic based PZT material named polyvinyl di fluoride (PVDF) because it can be moved with a little force and have the ability to handle high mechanical strain level without any damage [14]. It may be not feasible to use ceramic-based PZT material for the cantilever, as they are rigid, brittle, and heavy, causing restrictions in this kind of applications where flexibility is compulsory. Bluff body is made of solid silicon material to resist the flow to ensure von Karman's street pattern necessary to ensure continuous vibration of cantilever [11]. Table 4 presents the properties of material used in the finite element analysis, which is used for further analysis in this study.

Table 4. Material properties of fluid flow and energy harvester

Domain	Property	Numerical Value	Unit
Fluid	Density	100	kg/m^3
	Dynamic Viscosity	0.001	Pa. s
Bluff Body	Young Modulus	150	Pa
	Poisson's Ratio	0.33	
	Density	2330	kg/m^3
PVDF	Young Modulus	2	Pa
	Poisson Ratio	0.34	
	Density	1780	kg/m^3

Bernoulli Equation is used to calculate head loss and is represented in Eq. (7)

$$\frac{p_1}{\gamma} + z_1 + \frac{v_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{v_2^2}{2g} + H \tag{7}$$

where g is acceleration due to gravity, z_1 is elevation from the reference point at the inlet and z_2 is the elevation of reference point at the outlet; γ is unit weight of water, p_1 and v_1 are the pressure and velocity at the inlet, p_2 and v_2 are the pressure and velocity at the outlet respectively and H shows head loss. z_1 and z_2 are equal for in this analysis since the elevation from the inlet and outlet are same. v_1 and v_2 are approximately same, g is constant so Eq. (7) is further simplified to Eq. (8) for the head loss calculation.

$$H = \frac{p_1 - p_2}{\gamma} \tag{8}$$

4. COMPARATIVE ANALYSIS BETWEEN D AND I-SHAPED BLUFF BODY

Comparative analysis between D and I-shaped bluff body in terms of power output and performance impact on the pipe is carried out using PZT energy harvester in this section. As per analytical model presented in section 3 the maximum dimension of the bluff body (D) is 7.142 mm and length of cantilever (L) is 15mm. The thickness of the energy harvester (T) is 0.35 mm according to ratio taken in [25]. Meshing is an important part of the design and automatic meshing is done for this analysis since expected results came after applying this mesh. A sensitivity analysis with respect to the number of elements is performed for the mesh to ensure that the results obtained from finite elements model are correct. Fig. 4 shows a graph plotted between pressure difference across the surface of cantilever and number of elements of mesh produced in automatic physics controlled fluid dynamics mesh. It can be seen from the graph that pressure difference results asymptotically approach to a constant value after 4000 finite elements.

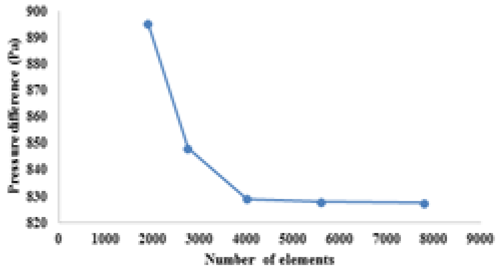
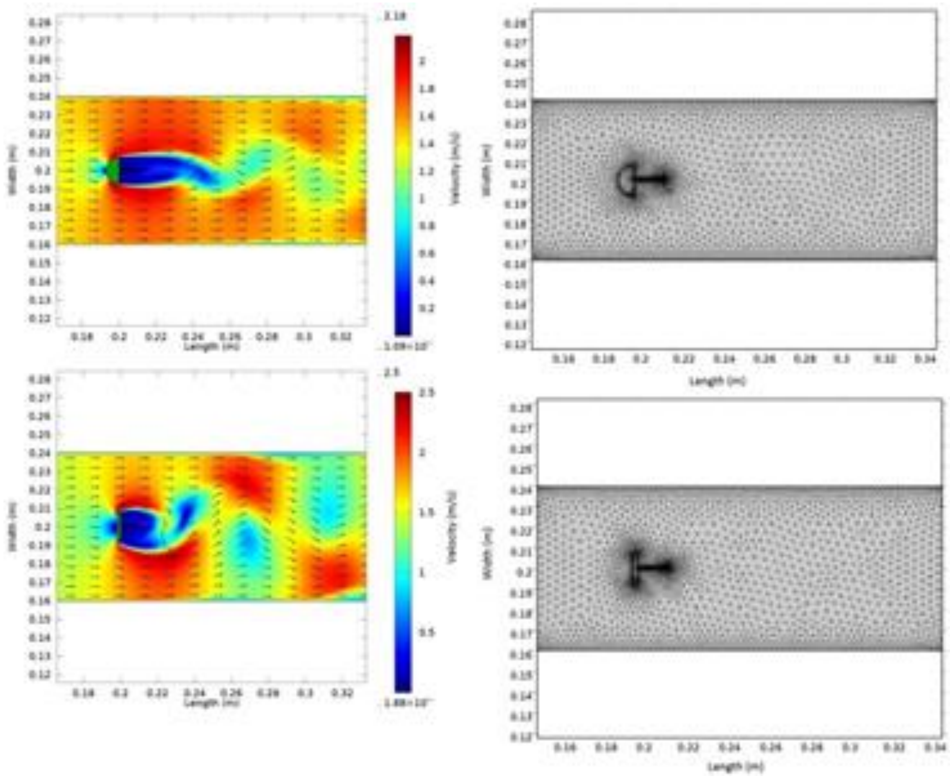


Figure 4. Sensitivity analysis involving pressure difference across the surface of cantilever versus number of mesh elements.

Fig. 1 (a) shows the generation of von Karman Street due to presence of energy harvester in the fluid flow. Velocity variation from 2.2 m/s to 0.2 m/s is produced near to the PZT energy harvester due to presence of D-shaped bluff body while variation from 0.1 m/s to 2.5 m/s is seen for the PZT energy harvester having I-shaped bluff body. Fig. 5 (b) shows the model of both D and I- shaped bluff body where uniformly distributed mesh is applied. The distribution of the mesh near to the bluff body is much finer as compared to other regions of the fluid domain which is the main point of interest in this analysis.



(a) (b)

Fig. 2 (a) Finite element results for both results for both D and I-shaped bluff body (b) Mesh for both D and I-shaped bluff body PZT energy harvester.

According to analytical predictions the frequency of the PZT energy harvester is 27 Hz and the pressure difference is 544 Pa. The power output from the analytical model is found to be 0.46 mW. Fig. 6 shows the 5 points to get the data of the pressure across the surface of cantilever for D-shaped bluff body. The spatial average of pressure is found from these points to approximate the pressure at the surface of cantilever. The line graph extracted from the 5 data points shows continuous pressure variation which is necessary to extract energy from the PZT harvester. The average pressure generated at the surface of D- shaped bluff body is found to be 828 Pa. Similarly, Fig.7 illustrates the points for PZT energy harvester having I-shaped bluff body and line graph shows that average pressure for I-shaped bluff body is 1630 Pa. Consequently, the useful electrical power is found to 2.24 mW for I Shaped and 0.82 mW for D Shaped bluff body.

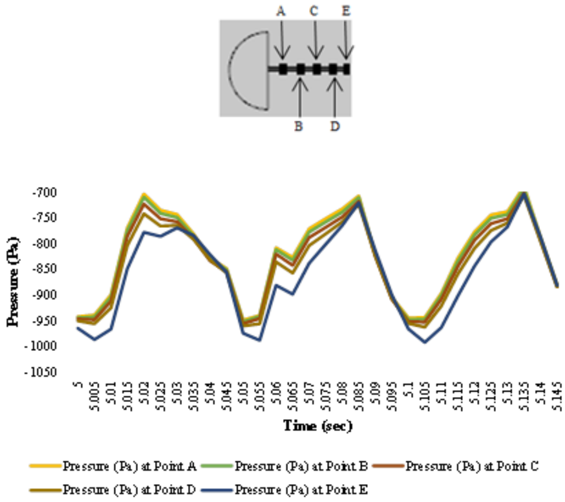


Figure 3 Extracted data points of pressure across the surface of D-shaped bluff body energy harvester layer from finite element simulation.

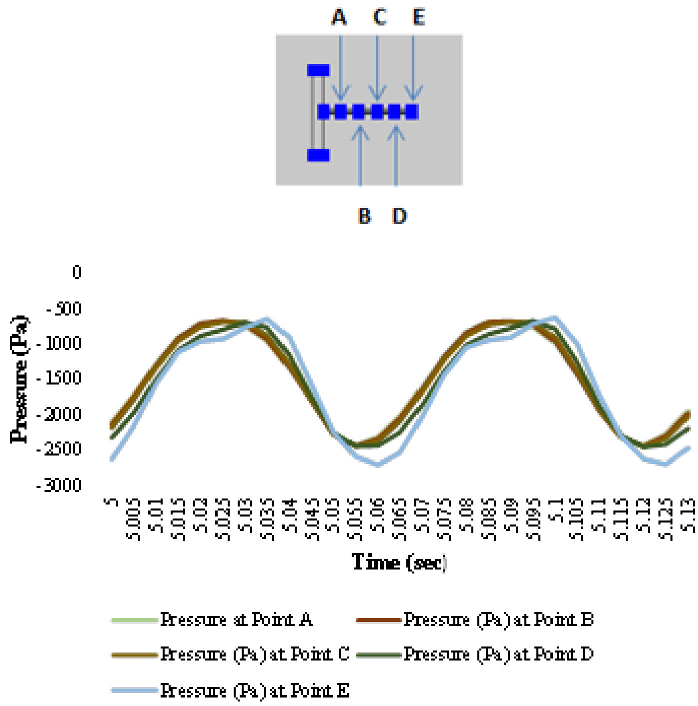


Figure 4 Extracted data points of pressure across the surface of I-shaped bluff body energy harvester layer from finite element simulation.

Performance impact on the pipe was performed by inserting 20 different points at outlet to estimate spatial average pressure. Spatially averaged-pressure for PZT energy harvester having D-shaped bluff body is calculated as 30 Pa using 20 points located on the inlet. As the unit, weight of water is 9807 N/m^3, the total head loss is found to be approximately 3 mm which is calculated by using Eq. (8). Head loss of 1.5 mm is found from finite element results without an energy harvester. The head loss increased to 3 mm when a PZT energy harvester is added to fluid domain which means an extra head loss of 1.5 mm, is introduced. While, pressure of 172 Pa is found at the inlet in the presence of I-shaped bluff body which means that head loss 17.2 mm is introduced due to presence of I-shaped bluff body. So PZT energy harvester having I-shaped bluff body offers 2.75 times more power at the expense of more than 6 times head loss which is not desirable so PZT energy harvester having D-shaped bluff body is chosen for sensitivity analysis.

5. SENSITIVITY ANALYSIS OF D-SHAPED ENERGY HARVESTER THROUGH FINITE ELEMENT SIMULATIONS

Finite element modeling and simulation results from three different sizes of the energy harvester are presented here in order to clarify the sensitivity of the analytically derived solution: 7.5 mm, 15 mm (analytically converged solution), and 22.5 mm. Fig. 8 presents the finite element simulation results. It can be observed that von Karman's Street is generated in Fig. 8(a) and 8(b). Since the length is reduced to half in Fig. 8(a), electrical power output has decreased and pressure increased on the beam, making this less a less desirable option. On the other hand, Fig. 8(c) shows that there is no von Karman's street generation, which is necessary for continuous vibration of beam to produce electrical power. The analysis confirms the length to dimension ratio defined in Eq.(2) for generation of electrical power at its peak from piezoelectric energy harvester.

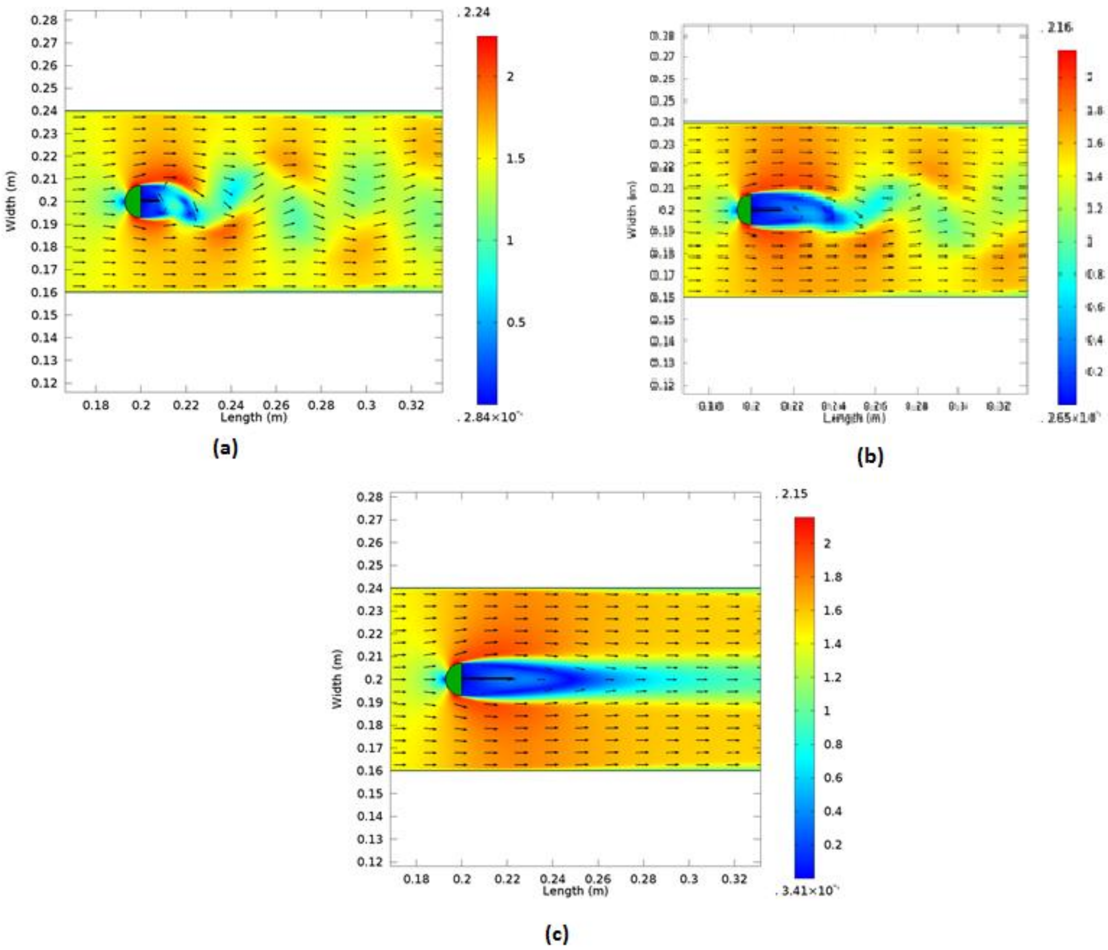


Figure 5. Finite element simulations of energy harvester with (a) 7.5 mm length (b) 15 mm length (c) 22.5 length.

Table 5 summarizes the results from the described three extreme points, plus few intermediate values. As observed, maximum power obtained is 0.82 mW for a length of 15 mm, and minimum power is 0.02 mW for a length of 6 mm. The finite element simulation results of pressure are significantly varied from the analytical calculations, because the dimension of bluff body plays a critical factor which is missed in the Bernouli Eq. (7) utilized in analytical models. Similarly, analytical calculations using Eq.(2) match closely to finite element simulation results when L to D ratio is consistent, which is not the case as the energy harvester size is scaled up. For a length of 5 mm finite element software gives error due to very short length and for 22.5 mm length pressure oscillations are damped which means that cantilever beam will not be able to vibrate continuously. A simulation with a length of 17.5 mm is also performed but tip displacement results are not periodic thus frequency cannot be calculated. So, 15 mm length is considered to be near optimal length, which is also consistent with the analytical predictions.

Table 1 Comparison of power output of analytical calculations and sensitivity analysis through finite element software.

Length of energy harvester (mm)	Simulation power found (mW)	Analytical Power Calculated (mW)
15	0.82	0.46
14	0.56	0.36
13	0.42	0.29
12	0.33	0.25
8	0.065	0.06
6	0.02	0.028

6. CONCLUSION AND FUTURE WORK

This study focuses on the method for maximum power generation from fluid flow through piezoelectric energy harvesting. The method was demonstrated by using the boundary conditions of Turkish-Cyprus under-water pipeline, which has recently been constructed to deliver fresh water to the island. The dimensions of the energy harvester have been derived through analytical calculations, and were further verified through sensitivity analysis performed with finite element modeling in COMSOL. A number of simulations were performed to build insight into the generation range of the harvester. Finally, a specific solution was proposed to meet the requirements of a realistic submerged Wireless Sensor Node operating in the selected pipeline. In addition, comparative analysis is done between D-shaped and I-shaped energy harvester in order to determine which one of them is more feasible to install for pipelines. For this purpose, important parameters including useful electrical power output and performance impact on the pipe are compared and analyzed in detail to make an important conclusion. In addition, finite element analysis is done for the validation of analytical results which is one of the most important parts of this research. The results show that with an average water velocity of 1.4 m/s, the designed energy harvester having D-shaped bluff body is able to produce power of 820 μW at the expense of 3 mm head loss while PZT energy harvester having I-shaped bluff generates 2.24 mW and offers a head loss of 17.2 mm.

In this study, detailed finite element model of turbine is not investigated and power conversion interface implementation circuit detailed analysis is not done. In addition, finite element simulation of different energy harvesters connected to a single bluff body is not performed. The scope of this study is limited to the near optimal design method with minimum impact on the pipe performance where two types of bluff bodies are used for comparison. This study can be expanded by adding more shapes of bluff bodies which may further improve the results of this research. The comprehensive analysis shows that it is possible to install energy harvester having the capability to produce electrical energy to meet the power requirements of the WSN to monitor the Turkey-Cyprus Water pipeline project.

REFERENCES

[1] J. Heidemann, M. Stojanovic, M. Zorzi, Underwater sensor networks: applications, advances and challenges, *Phil Trans R Soc A*, 370(1958), 158–175, 2012.

[2] C.C. Elam, C.E. G. Padró, G. Sandrock, A. Luzzi, P. Lindblad, E.F. Hagen, Realizing the hydrogen future: the International Energy Agency’s efforts to advance hydrogen energy technologies, *Int. J. Hydrog. Energy*, 28(6), 601–607, 2003.

[3] A.K. Akella, R.P. Saini, M.P. Sharma, Social, economical and environmental impacts of renewable energy systems, *Renewable Energy*, 34, 390-396, 2009.

[4] O. Ercoskun, S. Karaaslan, Guidelines for ecological and technological built environment: a case study on Güdül-Ankara, Turkey, *Gazi Univ. J. Sci*., 24(3), 617–636, 2011.

[5] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: a survey, *Comput. Netw.*, 38(4), 393–422, 2002.

[6] F.U. Qureshi, A. Muhtaroglu, K. Tuncay, A method to integrate energy harvesters into wireless sensor nodes for embedded in-pipe monitoring applications, 5. Int. Conf. Energy Aware Computing Systems & Applications (ICEAC), 24-26 March 2015, 1–4.

[7] M. Lubieniecki, T. Uhl, Integration of thermal energy harvesting in semi-active piezoelectric shunt-damping systems, J. Electronic Materials, 44(1), 341-347, 2015.

[8] S. Firat, Application of efficient and renewable energy technologies in low cost buildings and construction, *J. Polytech*., 17(1), 1-2, 2014.

[9] R.N. Silva, L.M. Rato, J.M. Lemos, F. Coito, Cascade control of a distributed collector solar field, *J. Process Control*, 7(2), 111–117, 1997.

[10] M.A. Ahmad, Piezoelectric water drop energy harvesting, J. Electron. Mater., 43(2), 452–458, 2013.
[11] S. Pobering, N. Schwesinger, Power supply for wireless sensor systems, IEEE Sensors Conf., 685–688, Lecce (Italy), 26-29 Oct. 2008.
[12] J.F. Kazienko, I.G. Ribeiro, I.M. Moraes, C.V.N. Albuquerque, Practical evaluation of a secure key-distribution and storage scheme for wireless sensor networks using TinyOS, *CLEI Electronic Journal*, 14(1), paper 8, 2011.
[13] M. K. Stojcev, M. R. Kosanovic and L. R. Golubovic, Power management and energy harvesting techniques for wireless sensor nodes, 9. Int. Conf. Telecommunication in Modern Satellite, Cable, and Broadcasting Services, Nis (Serbia), 7-9 October 2009.
[14] H.D. Akaydin, N. Elvin, Y. Andreopoulos, Energy harvesting from highly unsteady fluid flows using piezoelectric materials, *J. Intell. Mater. Syst. Struct*., 21(13), 1263–1278, 2010.
[15] J. Qiu, H. Jiang, H. Ji, K. Zhu, Comparison between four piezoelectric energy harvesting circuits, *Front. Mech. Eng. China*, 4(2), 153–159, 2009.
[16] G.K. Ottman, H.F. Hofmann, A.C. Bhatt, G.A. Lesieutre, Adaptive piezoelectric energy harvesting circuit for wireless remote power supply, *IEEE Trans. Power Electronics*, 17(5), 2002.
[17] P. M. Glatz, L. B. Hörmann, C. Steger, and R. Weiss, Designing perpetual energy harvesting systems explained with rivermote: a wireless sensor network platform for river monitoring, *Electronic J. Structural Engineering*, 55–65, 2010.
[18] N. Mohamed, I. Jawhar, J. Al-Jaroodi, L. Zhang, Sensor network architectures for monitoring underwater pipelines", *Sensors*, 11, 10738-10764, 2011, doi:10.3390/s111110738 .
[19] H.A. Sodano, D.J. Inman, G. Park, Generation and storage of electricity from power harvesting devices, *J. Intell. Mater. Syst. Struct*., 16(1), 67–75, 2005.
[20] Q. Wen, R. Schulze, P. Streit, D. Billep, T. Otto, T. Gessner, The design of vortex induced vibration fluid kinetic energy harvesters, Proceed. PowerMEMS, Atlanta (USA), 2-5 Dec 2012.
[21] E. Bischur, S. Pobering, M. Menacher, N. Schwesinger, Piezoelectric energy harvester operating in flowing water, Proceed. SPIE, 7643, 76432Z–8, 2010.
[22] M.S. Bhuyan, B.Y. Majlis, M. Othman, S.H.M. Ali, C. Kalaivani, S. Islam, Development of a fluid actuated piezoelectric micro energy harvester: finite element modeling simulation and analysis, *Asian J. Sci. Res*., 6(4), 691–702, 2013.
[23] M.S. Bhuyan, B.Y. Majlis, S.H.M. Ali, M. Othman, M.S. Islam, Modeling and finite element analysis of a micro energy harvester, Int. Conf. Multimedia, Signal Processing and Communication Technologies (IMPACT), 293–296, Aligarh, 23-25 Nov. 2013.
[24] D-A Wang, H-H. Ko, Piezoelectric energy harvesting from flow-induced vibration, *J. Micromechanics Microengineering*, 20(2), 25019, 2010.
[25] S. Pobering and N. Schwesinger, A novel hydropower harvesting device, Proceed. Int. Conf. MEMS, NANO and Smart Systems (ICMENS), 480–485, 2004.