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Piezoelectric Power Output Predictions Using Single-Phase Flow to Power Flow Meters

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***Abstract*—**This research involved the utilization of fluid flow energy to predict power output using Lead Zirconate Titanate (PZT) piezoelectric stacks. The aim of this work is to extract energy from a controlled level of pressure fluctuation in single-phase flow which forms a part of the energy harvesting technology that powers flow meters. A device- Perspex box was developed and fixed to 50.8 mm rig to induce pressure fluctuation in the flow. An experimental test was carried out using the single-phase water flow in the developed rig in order to measure the power output generation from the piezoelectric stacks. 16 sets of experimental tests were conducted to ensure the maximum output result. The acquired signal of the pressure fluctuation was used to simulate the expected electrical output from the piezoelectric material. The results showed a maximum output voltage of 12 V with an instantaneous output power of 1 µW generated, when the pressure amplitude is 2.6 kPa at a frequency of 2.4 Hz.

***Keywords*—**Energy harvesting, experimental test, perspex rig, pressure fluctuation.

I. Introduction

MOST small-scale electronic instruments and devices use a low power source to operate. These require the use of electricity from either an electric source which may not be available at some locations, or traditional batteries in order to successfully function. However, these batteries are usually associated with short life span and a limited source of electrical energy especially when exposed to an elevated temperature. In addition, battery requires frequent replacement and recharging. Therefore, for the facilities to operate without interruption; it is necessary to provide energy source that can continuously operate and this is obtainable using the application of the energy harvesting principle. Energy harvesting refers to the act of capturing a free energy from the environment which could otherwise be wasteful. The wasted energy can be transformed into usable electrical output [1]. Most of the instrumentation technologies require low power input to operate. For example, the transmitter or receiver of ultrasonic flow meters normally operates with low power input which is usually supplied by batteries [2].

Continuous application of energy harvesting technology to power instruments will save a lot of energy and time. The ultrasonic flow meter with 12 V DC converter and 12 V cigarette style power connection cord was applied with a fully charged battery supply power to a maximum of 24 hours' operation before recharging. Some flow meters are designed to operate using low power input. An example of this type is the Rheonic Coriolis mass flow meter. Rheonic Coriolis mass RHE 14 flow meter was applied to measure fluid flow in a pipe using 8-24 V DC power supply. Similar model of the flow meter, RHE 07 panel mounted transmitter was used to measure flow with an input power of 230/115V AC [3]. A flow Differential Pressure Module (FDPM) was applied to measure a fluid flow using 12-24V DC, 300 mA operating with an AC/DC converter. The device involved flow rate input of 0-8 V to 24 V maximum for two pressure transducers of 4-20 mA [4]. Batteries of 9 V DC, 12.5 A in a Samson type 5024-1 differential pressure flow meter was applied with an input power supply of 230 V AC, 45-60 Hz measuring circuit of 4-20 mA and a 20 V at 20 mA transmitter supply [5]. The FDT-30 ultrasonic flow meter technology was designed to require power source that supply 11-30 V DC at a minimum of 0.25 A. This was connected to the positive supply wire and to the appropriate field wiring terminals in the flow meter [6]. Most of the flow meters operate with lower power input. However, the operation is continuous over a long period of time. The frequent recharging and replacement of batteries is a major expense for such flow meters. The application of energy harvesting technology to supply input power to the flow meters could save a lot of energy, money and time.

Three major technologies were used by Hao and Gracia [7] to develop a digital battery-free smart pipe flow meter. These technologies involved use of low power consumption metering unit, a cog-resistance free-generator with high efficiency and effective methodology to extract and store energy. A repeated experimental test was carried out with an airflow in 11 mm diameter pipe to drive a turbine at 10 revolutions per second. In the experiment, a flow of 20 revolutions per second for 720s was used to generate enough power for the flow meter without requiring a battery or any other external power. This research is similar to the present work; water was used in the experiment to achieve the result. A Perspex box was designed, developed and fixed to the rig to create fluctuation in the flow in order to extract energy.

Energy harvesting from fluid flow using piezoelectric or electromagnetic device is already a popular research field. The force of the fluid oscillation can be applied to generate electrical output using an energy harvesting device. Wang and Chang [8] have demonstrated vibration energy harvesting using pressure fluctuations applied to a permanent magnet. The result showed an output voltage of 10 mV_{PP} with amplitude of 254 kPa at a frequency of about 30 Hz. Under

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this condition of operation, an instantaneous power output of 0.4 μW was determined. This is similar to the work of Wang and Ko [9] where a finite element device was developed and applied to estimate the voltage generated by a piezoelectric film from flow induced vibration. The experimental result showed an output voltage of $2.2V_{PP}$ with an instantaneous output power of 0.2 μW when the pressure oscillates with amplitude of 1.196 kPa at a frequency of 26 Hz. Sarciada [10] designed a prototype of electromagnetic energy harvester from pressure variations induced in a pipe. An output power of 3.78 μW with output voltage rate of 40 mV was achieved at 3 kPa step pressure change. It can be deduced from many reviews that most of the results obtained for the output voltage and power were in digit voltage and micro units' power [8]-[10].

One of the methods of energy harvesting that involved the conversion of mechanical energy of vibration into electrical energy was achieved by the use of piezoelectric material. The application of piezoelectric devices has produced significant benefits in micro power systems. The principle involved in piezoelectric conversion is related to the deformation of the piezoelectric material to generate an electric field and hence a voltage drop proportional to the stress is applied [11]. Guigon et al. [12] described experimental device that uses piezoelectric flexible structures to capture the vibration energy affected by a water droplet. Theoretical study was applied to optimize the mechanical system. The experimental device was used to validate the result. Sodano et al. [13] presented a review on power harvesting from vibration using piezoelectric materials. Piezoelectric material has crystalline structure that provides them with the ability to transform the mechanical strain into electrical charge. Piezoelectric materials are the most applied technology in the field of energy harvesting.

Wang et al. [14] used the oscillation of piezoelectric films to convert the flow energy into electrical energy by a new energy harvester. The harvester was used to transform the energy from Karman Vortex Street behind a bluff body in a flow of water. Based on the experimental results, an output voltage of $0.12V_{PP}$ and 0.1 nW instantaneous power were generated using pressure oscillation with amplitude of 0.3 kPa at a frequency of about 52 Hz. The output power potential can be optimized by the use of a piezoelectric material with high piezoelectric coefficient. Pang et al. [15] carried out a study for the optimization of an interface circuit in a piezoelectric energy harvesting system. The result was achieved through simulation implemented in Pspice which included parametric sensitivity and optimization analysis. The result showed that energy collection performance can be improved by using optimization simulation method. Lee et al. [16] investigated designs of two piezoelectric transducers applied to fluid motion and coupled to structural vibration through a cantilever placed in the converging-diverging flow channel. The two designs consist of bimorph and the flex tensional clamps, a non-piezoelectric cantilever provided the force required to produce electricity. The designs were used experimentally to generate power at a level of 20 mW and above. Other methods involve the use of fluidic device to generate fluctuation in the flow in order to extract the energy. The frequency and energy in fluid oscillation can be obtained when the fluid flows across a fluidic device in a cylinder. In this case, the interest lies in the relationship between the frequency component of the fluid force and the corresponding responses. The cylinder experiences pressure generated during a previous cycle [17]. Piezoelectric energy harvesting from vertical beam in low and high speed flows has been investigated by Amini et al. [18]. In contrast to the low speed flows, the extracted power from vertical beam in the high speed flow was considerable. Energy harvesting from piezoelectric Gurney flap attached to a NACA2412 air flow was investigated for vertical beam in high speed flows. The piezoelectric vertical beam with an attached end cylinder was proposed as the energy harvester in a slow speed flow. It indicates that the device has a strong vibration and should therefore produce a remarkable electric power. The result obtained in this paper is similar to the ones achieved in the existing reviews. However, the present work further indicated that the output result can be optimized to greater output of voltage and power. In addition, for higher output predictions, the system may involve the application of a fluidic device in the Perspex box to generate more pressure fluctuation.

II. Materials and Methodology

The methodology employed in this work involved the use of Perspex box in the flow line. The Perspex box was designed, constructed and mounted to the 50.8 mm rig single-phase flow to create pressure fluctuations in the flow. The water flows into the Perspex box to generate turbulence due to change in flow area and the pressure in the box fluctuates instantaneously. Pressure fluctuation signals were obtained experimentally from the flow. The pressure signals acquired were used to predict the amount of the energy generation using piezoelectric materials. Samples of PZT piezoelectric stack were considered to investigate the electrical output that will be generated when compressed. The compression force is derived by the pressure fluctuation enabling the fluid to instantaneously strike the piezoelectric stack. Fig. 1 illustrates the schematic diagram on how the energy harvesting system works to extract the electrical output. The energy harvester operates as a system of pistons in a cylinder. In this case, the PZT material is compressed by the force of the fluid fluctuation, which can produce certain deformation in the direction of the applied force (-33 mode) required to extract electrical output. The -33 mode indicated that the force is applied in the polar direction. Larger strain provides greater mechanical energy for conversion. Roundy et al. [19] presented -33 and -31 mode operation for piezoelectric material. The -31 mode is the most commonly used coupling mode, however, -33 mode yields greater coupling coefficient. Yang et al. [20] have shown that the output power of piezoelectric plate operating in -33 mode is proportional to the coupling coefficient and the dielectric constant. This shows that devices that have a higher coupling coefficient produces greater power and behave more efficiently [21]. The present method is unlike that of Wang and Chang [8], Wang and Ko [9] in which vibration energy was used to extract the electrical output using piezoelectric materials. In this work, the direct force of the pressure fluctuation in the Perspex box was applied to simulate the energy output from the piezoelectric material. The device operates as oscillating system. The fluid flows as a continuous oscillating force which instantaneously forces the piston to compress the piezoelectric stacks there by generating a charge or voltage output. The equation of motion for the oscillation to deform the mass m of the piezoelectric material due to pressure fluctuation is expressed in (1) and (2):

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = F(t) \tag{1}$$

$$F(t) = P_F A \tag{2}$$

where P_F is the pressure fluctuation occurring in the Perspex box and A is the area of the opening through which the force strikes the stack. b is the damping coefficient and k is the spring constant when considered as a spring mass and damper system. These constants are incorporated in the compression or coupling coefficient and mechanical factor of the piezoelectric materials.

The PZT piezoelectric stack is compressed by the force through its area as illustrated in Fig. 1. The electrical output extract is strictly depending on the magnitude of the force applied to the piezoelectric material and the direction of the polar axis. When the piezoelectric material is deformed or squeezed, electric charge and voltage are generated between the surfaces of the material. An alternating electrical output is obtained for the continuous pressure fluctuations [13]. The electric charge (Q_C) and voltage (V_T) generation are related to the piezoelectric coefficient and properties defined by the expressions in (3):

$$Q_C = Fd_{33} \text{ and } V_T = Fg_{33}\, {}^{t}\!/_{l} \tag{3}$$

where d_{33} and g_{33} are the strain and voltage coefficient, t, l and w are the thickness length and width of the piezoelectric stack. The power output of the piezoelectric stack is given by the expression in (4):

$$P_{PZT} = 0.5Q_C\, {}^{V}\!/_{T} \tag{4}$$

where P_{PZT} is the power generated by the piezoelectric stack and T is the period at a frequency of the maximum pressure amplitude, V is the output voltage [22]. Properties of the various forms of the PZT piezoelectric stack were considered and applied in order to predict the electrical output generation.

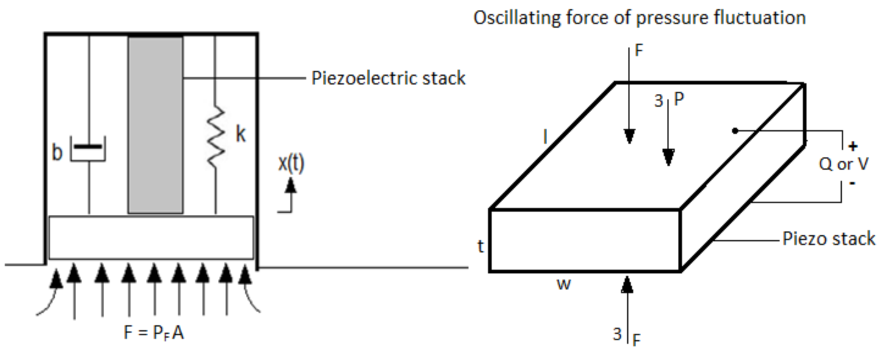


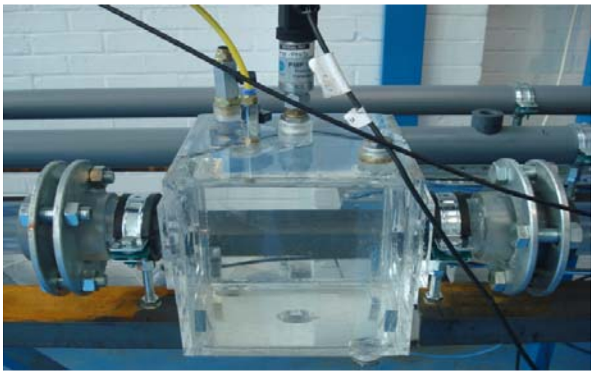
Fig. 1 Schematic diagram of the piezoelectric energy harvesting system

TABLE I
THE PROPERTIES OF SOME SELECTED MODELS OF PIEZOELECTRIC STACKS

PZT Model	Density (kg/m^3)	Strain coefficient d_{33} (C/N)	Voltage coefficient g_{33} (Vm/N)	Coupling coefficient k_{33}(C/N)	Mechanical quality factor Q_m
NCE 40	7750	320E-12	27E-12	0.70	700
NCE 51	7850	443E-12	26E-12	0.74	80
NCE 55	8000	670E-12	19E-12	0.72	70
PSI 5H4E	7800	650E-12	19E-12	0.75	30

The properties of the piezoelectric stack such as the strain, voltage and the coupling coefficient were applied to simulate the expected power output. These properties were obtained from the models of the piezoelectric stacks shown in Table I. and applied in (3) and (4) to obtain the result. The result is highly depended on the amplitude of the pressure fluctuation and the strength of the piezoelectric stack determined by the properties [23]. The objective of this work is to create a Perspex box, which is a device that induces pressure fluctuation. The box is made of Perspex material having a dimension of 0.2 X 0.22 X 0.24 m. The device was made with three holes at the top and bottom for pressure tapings and to drain the water out of the box after some sets of experimental tests. The box was designed to consisting of openings to which flanges are coupled in order to fit the pipe connections upstream and downstream flow. The main aim of the box is to create turbulence forming a source to which energy can be extracted. Tests of different flow rate were carried out to achieve a higher turbulence with various instrumentation systems set to measure the data for each test. Fig. 2 (a) illustrates the Perspex box fixed to the flow line to generate the pressure fluctuation. Fig. 2 (b) shows the Lab-view software data acquisition system applied to obtain the signal. The experimental tests were carried out using the flow of 18, 21.6, 25.2 and 28.8m^3/hr at interval of 180 seconds for a round of test. The amplitude signals of the fluctuating pressure were used to estimate the magnitude of the compressive force. This is required to predict the electrical output capacity using the models of PZT piezoelectric material. The piezoelectric stack of same area of 0.0036 m^2 and varying thickness of 0.02 m interval were considered to investigate the electrical output that can be generated from the stack. Figs. 3, 4 showed how the pressure signals were transformed into signal power and amplitude of the pressure fluctuation generated in the Perspex box. The signal power and the amplitude were acquired in similar way as in the work of Mukhtar et al. [24].

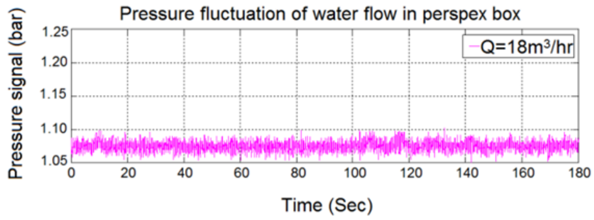
The pressure signal data were obtained through the repeated experimental test using the same flow rate input of the 180s for data analysis. The system consists of flow meters, temperature and pressure transducers fixed in order to sense and record data. The amplitude pressure was determined using the First Fourier transform (FFT) of the pressure signals. The pressure signals acquired were used to simulate the electrical charge, output voltage and power using the sample of the PZT piezoelectric material. The FFT of the pressure signals were illustrated as shown in Figs. 3, 4.



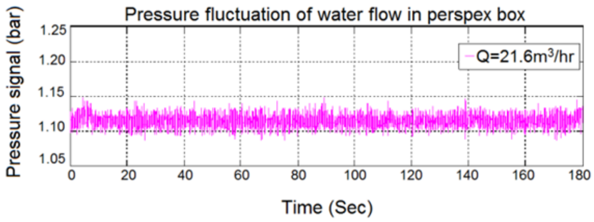
(a) Section of the Perspex box fixed to flow line

(b) Instrumentation and data acquisition systems

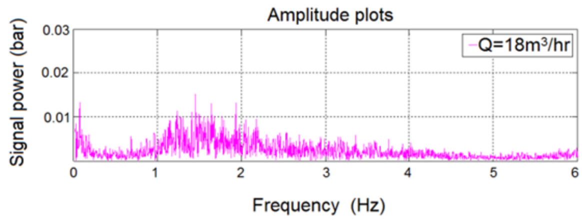
Fig. 2 Experimental text set-up to create pressure fluctuation in a single-phase flow



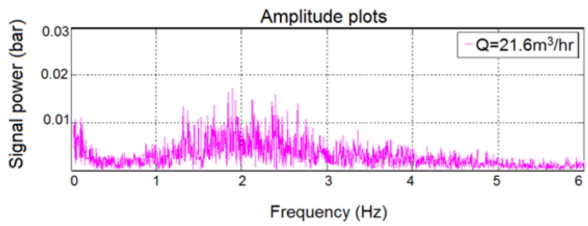
(a) Plot of pressure fluctuation in Perspex box for Q=18 m^3/hr



(b) Plot of pressure fluctuation in Perspex box for Q=21.6 m^3/hr

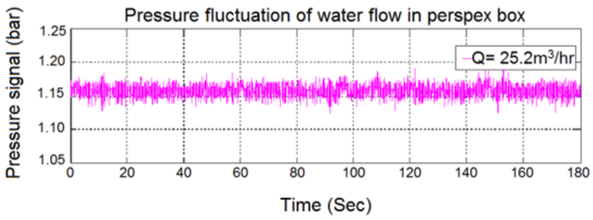


(c) Amplitude plots for Q=18 m^3/hr

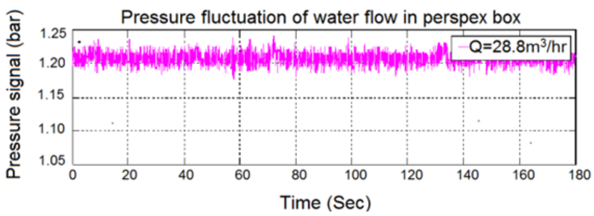


(d) Amplitude plots for Q=21.6 m^3/hr

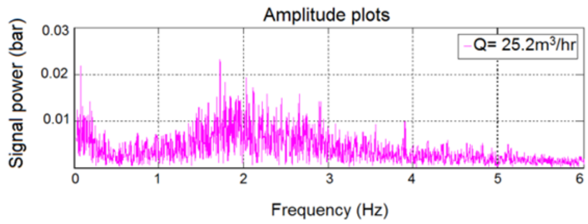
Fig. 3 Plots of pressure fluctuation FFT of the instantaneous pressure



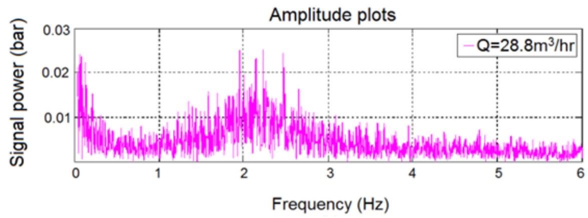
(a) Plot of pressure fluctuation in Perspex box for Q=25.2 m^3/hr



(b) Plot of pressure fluctuation in Perspex box for Q=28.8 m^3/hr



(c) Amplitude plots for Q=25.2m^3/hr



(d) Amplitude plots for Q =28.8m^3/hr

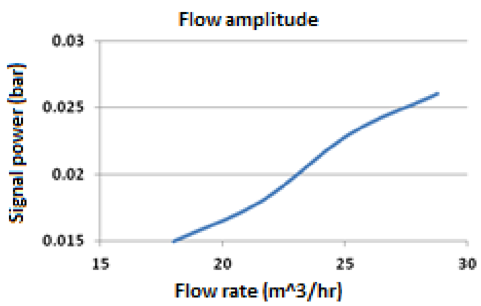
Fig. 4 Plots of pressure fluctuation FFT of the instantaneous pressure

III. Results and Discussion

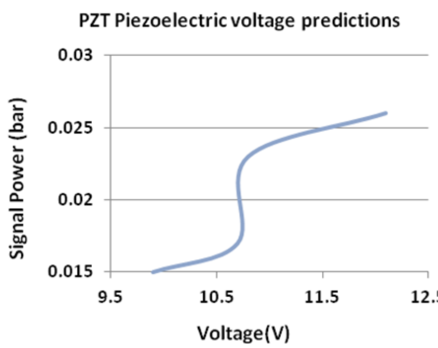
Table II showed the predicted electrical output results. The electrical output obtained using the PZT piezoelectric materials were investigated by considering pressure fluctuations for the flow rate of 18 to 28.8 m^3/hr. as the source of energy. It can be observed form Table II that the maximum amplitude of the pressure signal is 0.026 bar correspond to a voltage difference of approximately 12 Volts. This shows that greater electrical output was generated at higher flow rate. The peak amplitude was obtained at maximum flow rate giving the highest output voltage and power in the test. It can be seen in Table II that the amplitude of the pressure fluctuating does not vary much and produced a close range of power output. The predicted electric charge, output voltage and power were obtained from the simulation using the models of piezoelectric stacks. The pressure amplitudes were obtained from the signal power applied to achieve the result. This shows the interdependency of the electrical outputs with the signal power required to harvest the energy. It can be observed from Fig. 5 (a) that the flow rate varies directly proportional to the signal power. Moreover, the signal power was also related to the output voltage as shown in Fig. 5 (b). Also the signal power obtained from the flow rate is related to the output charge and power shown in Figs. 6 (a), (b). The signal power is a function of the flow rate and the highest electric charge was obtained at the maximum flow rate. Alternatively, the maximum power output was achieved at a flow rate of 29 m^3/hr. This shows that the electrical output is directly related to the signal power generated in the Perspex box. The output voltage and power strictly depend on the intensity of the signal power controlled by the amount of fluctuation created. The magnitude of the generated electrical output increases as a result of increase in the flow rate. Increase in the flow rate produces more pressure fluctuation hence higher power output could be achieved. The result shows a maximum output voltage of 12 V with an instantaneous output power of 1 μW generated when the amplitude pressure is 2.6 kPa at a frequency of 2.4 Hz.

TABLE II
The Predicted Electrical Output Using the PZT Piezoelectric Stacks

PZT Model	Flow rate (m^3/hr.)	Peak amplitude (bar)	Peak frequency (Hz)	Charge generated (Q)	Voltage generated (V)	Power generated (W)
NCE 40	18.0	0.015	1.46	2.11E-08	9.9	1.58E-07
NCE 51	21.6	0.017	1.90	3.11E-08	10.7	3.38E-07
NCE 55	25.8	0.023	1.73	6.78E-08	10.8	6.24E-07
PSI 5H4E	28.0	0.026	2.43	7.44E-08	12.1	1.04E-06

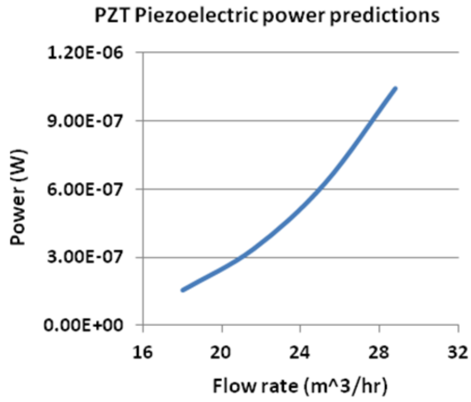


(a) Signal power as a function of the flow rate

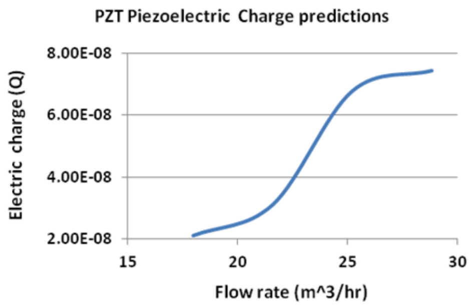


(b) Output voltage predictions

Fig. 5 Signal power for electrical output predictions



(a) Output power predictions



(b) Electrical charge predictions

Fig. 6 Predictions of electrical output from PZT Piezoelectric material using single-phase flow

IV. Conclusions

This paper showcased the application of energy harvesting techniques using single-phase flow to power flow meters. The development of a Perspex box that actualized the harnessing of energy, based on the flow was carried out. The Perspex box was fixed to a 50.8 mm horizontal pipe; hence pressure fluctuations in the flow line were created. The acquired signal of the pressure fluctuation was applied in order to simulate the expected electrical output using the PZT piezoelectric stacks. The result showed a maximum output voltage of 12 V with an instantaneous output power of 1 μW, generated when the pressure amplitude is 2.6k Pa at a frequency of 2.4 Hz. For better output, the efficiency of the system was maximized by fixing a fluidic device in the Perspex box, which also generated a higher level of pressure fluctuation.

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