Evaluation of Energy Harvesting Potential in Water Pipelines to Power Sustainable Monitoring Systems

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Abstract

About 20% of treated drinking water is estimated to be lost in the U.S. through distributation pipeline leakage. Current leakage detection technologies are expensive, operator-dependent, time consuming, and they only reveal the snapshot status of the pipeline at the time of inspection. There is a growing interest in employing inexpensive wireless sensor networks (WSNs) to continuously monitor distribution pipeline networks and detect significant leakages in near real-time. The lack of a sustainable energy source in buried pipeline environment to power the monitoring WSNs remains to be a great challenge. This paper presents the results of a systematic experimental evaluation of the energy harvesting potential from the flow-induced vibrations of a two-looped, real-size pipeline test bed that comprises varying pipe sizes, multiple bends, T-joints, and valves. The primary objective of this paper is to determine how much energy can be harvested from the pipeline's surface vibration and subsequently determine how variable this energy is across the two-looped pipeline network. Piezoelectric films are mounted on the pipeline surface at different locations to simultaneously collect vibrations-induced energy data. Various experimental configurations were used to evaluate the variation of energy harvesting potential across locations closer to the bends, T-joints and along straight sections of the pipeline. Results reveal the feasibility of harvesting some energy from pipeline vibrations and it is also observed that harvestable energy varies with harvesting location across a pipeline network as well as the pipe flow.

INTRODUCTION

About 20% of treated drinking water is estimated to be lost in the U.S. through distribution pipeline leakage (Yazdekhasti et al., 2016). Current leakage detection technologies are expensive, operator-dependent, time consuming, and they only reveal the snapshot status of the pipeline at the time of inspection. There is a growing interest in employing inexpensive wireless sensor networks (WSNs) to continuously monitor distribution pipeline networks and detect significant leakages in near real-time. The lack of a sustainable energy source in buried pipeline environment to power the monitoring WSNs remains to be a great challenge. While batteries are useful power supply sources, they need to be replaced periodically and they are environmentally harmful (Ye & Soga, 2012)(Mohamed et. al., 2011). Recent studies evaluated energy harvesting potential using solar, hydropower (Ye & Soga, 2012), and flow induced vibration (Wang & Ko, 2010) (Pobering & Schwesinger, 2008). Wang & Ko (2010) proposed a device with pressure chamber and flexible diaphragm for small diameter pipes to enhance the flow induced vibration for energy harvesting. Pobering and Schwesinger (2008) used a cantilever piezoelectric film in a wind channel to harvest energy from airflow. While availability of harvestable energy is one challenge, its variation with time is another challenge that makes it less reliable. Data collection and transmission frequencies along with transmitted data size determine the power requirements of a pipeline monitoring system. It was reportedly estimated that tens of milliwatts (mW) of power is required when sensors in U.K. water companies recording data every fifteen minutes transmit data to a control center every 30 minutes (Ye & Soga, 2012). Yazdekhasti et al. (2016) proposed a leakage detection index which uses the cross spectral power densities of two or more accelerometers in order to detect leakage in a pipeline. A standard modern sensor system, such as an accelerometer coupled with a microcontroller, would require relatively low voltages in the order of about 1.8V (for example, if we use an ADXL362 with a MSP430FR5969 - both require 1.8V supply voltage).

In this paper, harvestable flow-induced pipeline vibrational energy is assessed using piezoelectric films. Piezoelectric films are attached on the pipe surface using a clamp kit in this study. A cantilever piezoelectric film is used for long-lasting vibrational effect to maximize harvestable energy (Priya, et al., 2017). The objectives of this study are to determine (a) how much energy can be harvested across the pipeline system complexities such as smooth bends, T bends, joints, and straight section, and (b) how the energy harvesting potential varies with location and pipe size.

METHODOLOGY

A two-looped pipeline network with varying diameters, multiple bends, T-joints, and valves has been used as an experimental test bed in this study. This pipeline network, which is representative of a real-world system, is connected to a pump (Dayton model of 3KV80A) located at an elevated platform which draws water from a 420-liter reservoir. The schematic layout of this experimental setup is depicted in Figure 1. The solid line in Figure 1 depicts the 32 m long, 76 mm diameter PVC pipe and the broken line depicts the 102 mm diameter PVC pipe. Both loops are placed at an average depth of 0.6 m over sand-cushion bedding in the ground. A magnetic flowmeter (FMG3002-PP-D) is attached on the 76mm diameter pipe in order to measure the flow in the system.

This study attempts to harvest electrical energy from mechanical energy (of flow induced vibration) using direct piezoelectric effect. When piezoelectric material is compressed or squeezed by mechanical stress, it generates piezoelectricity. In this study, flow induced surface vibration is considered as the primary source of mechanical energy for piezoelectric material. A piezoelectric film (MIDE PPA 1021) is selected that can work with low frequency vibrations with acceleration ranging from 0.25g to 1g. The monitoring locations where piezoelectric films are attached along the two-looped pipeline network are illustrated in Figure 1. The piezoelectric films have been used along with the PPA 9001-clamp kit, as shown in Figure 2, to configure different tip mass combinations for varying pump frequencies. One of the reasons for using piezo PPA 1021 is that when it is used with the chosen clamp kit, tip mass can be altered to lower the piezo's resonant frequency to match with that of the pipeline system for maximum energy output. The piezoelectric produces maximum power at its resonance frequency because both the power density and efficiency of piezoelectric film used in vibrational energy harvesting are intensely frequency dependent (Li et. al., 2014).

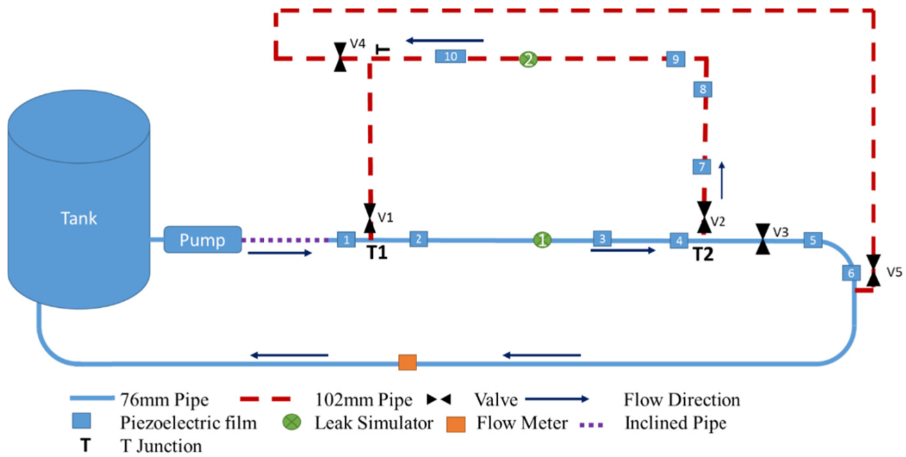

Figure 1. Schematic layout of the experimental pipeline set-up

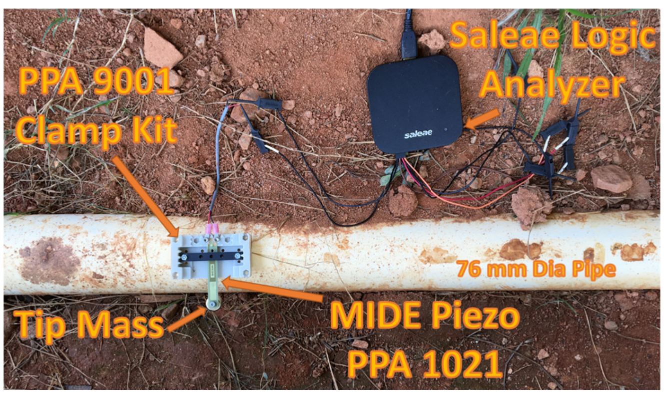

Figure 2. MIDE PPA 1021 piezo attached on 76 mm diameter pipe along with logic analyzer

It is reasonably assumed that the natural frequency of the pipeline system would be same as the pump frequency. According to the specifications of piezo PPA 1021, the resonant frequency with 12.7g tip mass is 23Hz and with 1.7g tip mass is 60Hz (MIDE Piezo, 2017). The frequency of the pump used in this study can range between 0Hz and 60Hz. Four different pump frequencies are initially used in this study; they are 22Hz, 33Hz, 43Hz, and 53 Hz. As shown in Figure 2, the piezo is clamped on to the kit with tip mass of 12.8g (which is the closest possible mass increment to 12.7g) to make the piezo's resonant frequency 23Hz when the pump frequency is 23 Hz. The piezoelectric film is connected to Saleae logic analyzer (16 channel) to record the output voltage. Saleae has a 12-bit analog to digital convertor (ADC) inbuilt for every channel. It can measure signals ranging between -10V to 10V from each channel. The ADC converts the incoming analog signal into a digital value. It has analog sampling rates ranging from 10Hz to 50MHz and digital output range 0 (digital) for -10V(analog) to 4095(digital) for +10V(analog). The resolution of the device is 4.88mV/LSB, which means every increment of the analog signal by 4.88mV will result in an increase in the digital output by 1 unit.

The energy harvesting analyses has been conducted using four scenarios in this study. Experimental configurations of each scenario are specified in Table 1. The experiments in all four scenarios were carried out for three different pump rotational frequencies (23Hz, 33Hz, and 43Hz) in order to evaluate the effect of pipeline flow rate on the energy harvesting potential.

Table 1. Configuration of the experimental set-up for various scenarios

Scenario	Valve Configuration	Targeted Locations
Scenario 1	V1 and V3 Closed	Straight on 76mm diameter pipe
Scenario 2	V1, V2 and V5 Closed	Straight vs Smooth Bend
Scenario 3	V1 and V3 Closed	Straight vs Sharp Bend
Scenario 4	V1 and V3 Closed	Straight vs Tee Bend

SCENARIO ANALYSIS: RESULTS AND DISCUSSION

Initially, the root mean square (RMS) value of piezo #2 (see Figure 1) has been calculated for 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, and 90 second intervals at a pump frequency of 23Hz to determine the optimum data sampling interval. The RMS values were found to be approximately same for all the studied intervals, and subsequently a 15-sec interval has been chosen as a standard for this study. The data sampling frequency is 5000 Hz. Mean RMS values from ten sets of 15-second samples are calculated to avoid any statistical or human errors. Furthermore, data from multiple monitoring locations were recorded when the flow meter reading is approximately same to ensure comparable physical conditions in the test bed.

It is found in the preliminary investigation that changing the tip mass for a small resonance frequency differential (say 10Hz) does not result in considerably different output voltages. Although the RMS values were found to be somewhat different, output voltage (peak-to-peak) signal was a pure sine wave for 23 Hz but other frequencies resulted in noisy signals with random peaks, as shown in Figures 4 and 5 for piezo 1, 2, and 3. The peak-to-peak voltage output plots help to understand the nature of energy output. A pure sine wave results in higher RMS voltage and provides stable D.C. voltage. Based on the peak-to-peak voltage output, it has been determined that the voltage output signal at only 23Hz seemed like a pure sine wave.

Scenario 1

Valves V1 and V3 are closed in this scenario and as a result, flow gets diverted from the 76 mm pipe to 102 mm pipe through valve V2. Vibrational energy measured through piezos labeled 1, 2 and 3 are considered to investigate the straight pipe section in this scenario. The RMS voltages of piezos 1, 2 and 3 at pump frequencies 23Hz, 33Hz 43Hz and 53Hz (53Hz only for piezo #2) are shown in Figure 3.

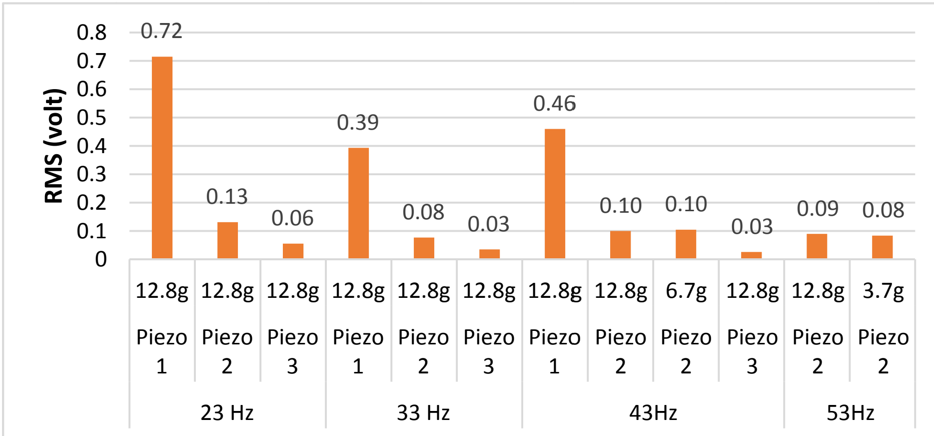

Figure 3. Comparison of RMS (volt) at different locations on straight section

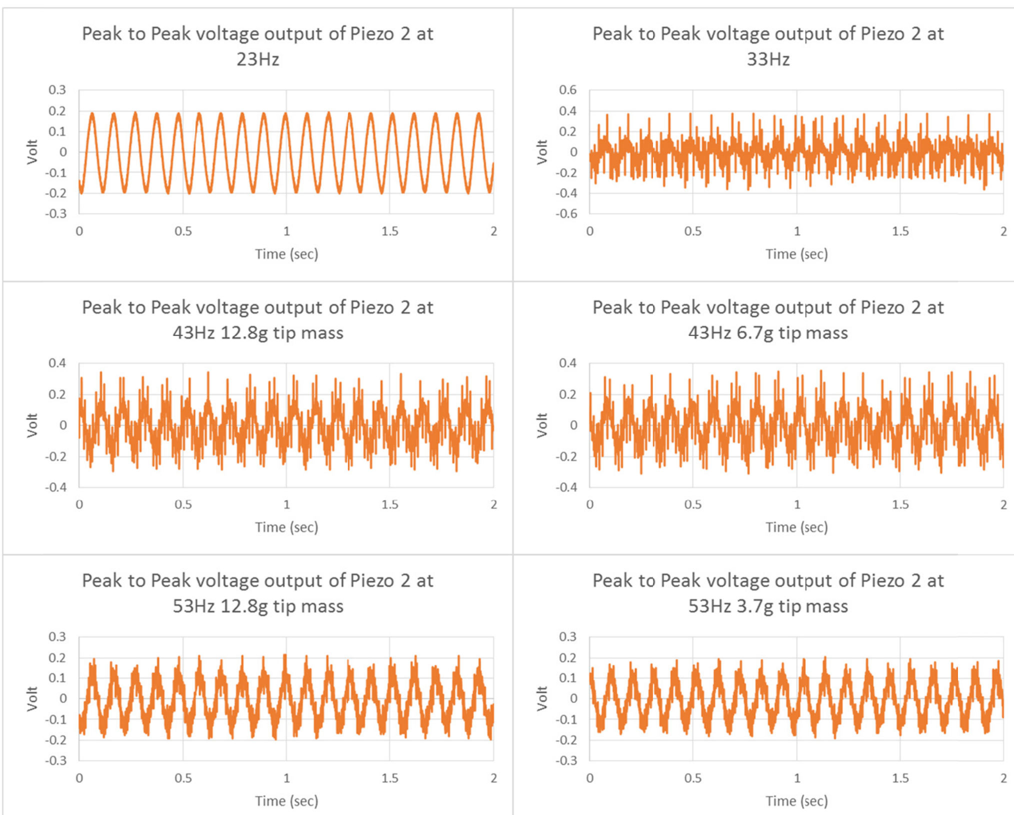

Figure 4: Peak to peak voltage output of piezo #2 at 23Hz, 33Hz, 43Hz, and 53Hz pump frequencies and different tip masses

The 76mm diameter pipe is connected to the pump (placed at an elevated surface) with an inclined pipe of same diameter, as illustrated in Figure 1. It is believed that the change in resulting vertical flow direction has caused considerable turbulence that resulted in high RMS voltage from piezo #1. The impact of turbulence is expected to dissipate with distance and this is believed to have resulted in lower RMS voltages for piezos 2 and 3 compared to piezo 1. In addition to the commonly used 12.8g, appropriate tip masses were calculated and used for pump frequencies 43Hz and 53Hz as per the specifications of Mide piezo PPA 1021. These additional tip masses did not make significant difference in output RMS voltage, as can be observed from Figure 3. Piezo #2 with tip masses of 6.7g and 12.8g at 43Hz have resulted in similar RMS voltage values, as can be seen from Figure 3 and similar peak-to-peak voltage output signals, as can be seen from Figure 4. The RMS voltages are slightly different for 53Hz pump frequency as can be seen from Figure 3, but the peak-to-peak voltage output signals are similar, as can be seen from Figure 4. Because the resonance frequency of the piezoelectric film is 23Hz with 12.8-gram tip mass, maximum RMS voltages are observed at this frequency for all the three piezos (1, 2 and 3).

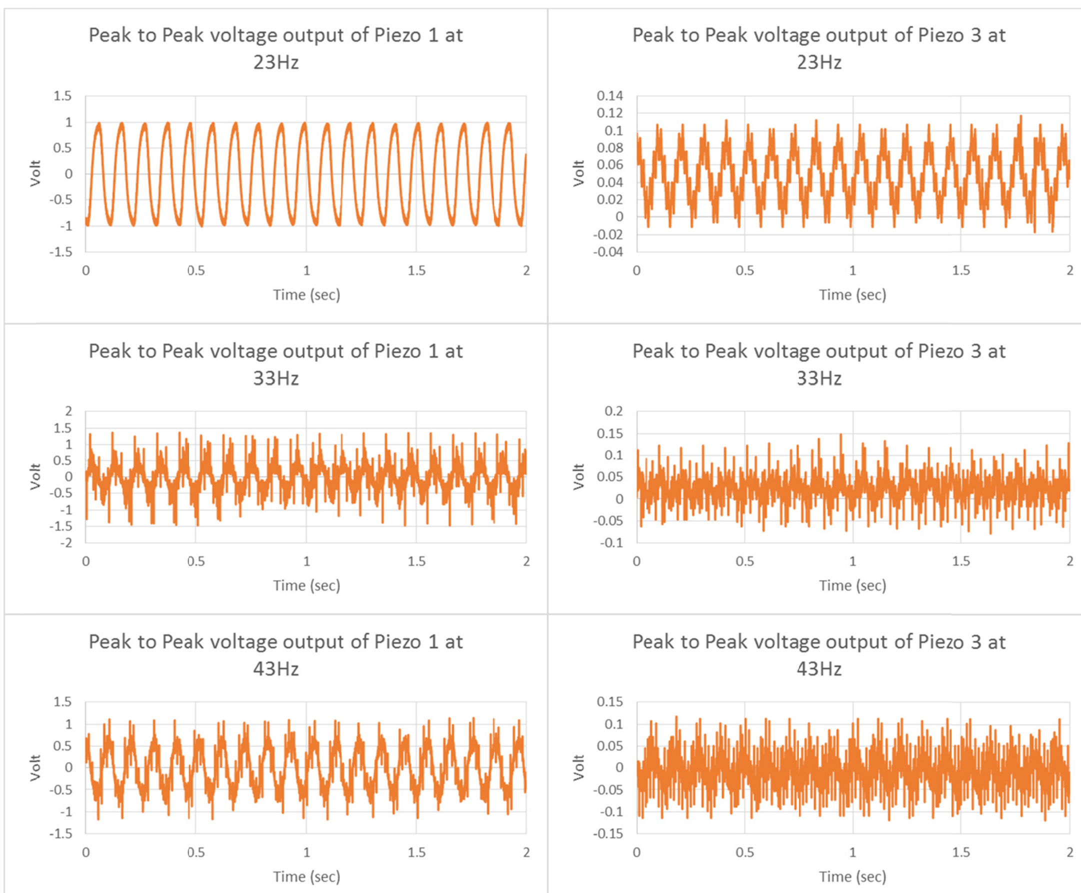

Figure 5: Peak to peak voltage output of piezo #1 and piezo #3 at 23Hz, 33Hz, and 43Hz with 12.8-gram tip mass

The peak-to-peak voltage output at 23Hz is maximum and the signal shows a pure sine wave, as can be seen in Figures 4 and 5 for piezos 1, 2 and 3. A pure sine wave output from a piezo is ideal as it enables the best conversion to a stable D.C. voltage (Nova Electric, 2017). In an uneven sine wave, some peaks have maximum value but some have less, so it reduces the overall RMS value. Scenarios 2 to 5 present results from only 23Hz pump frequency to appropriately understand the harvestable energy and its variation across the system.

Scenario 2

Valves V1, V2 and V5 are closed in this scenario allowing flow only in the 76mm loop. Three piezoelectric films labelled 3 (on straight section), 5 and 6 (before and after smooth bend, respectively) are placed on the pipe surface along the 76mm loop. Resonance frequency of the piezoelectric film is matched with the pump frequency of 23Hz.

The RMS values of voltage output from piezoelectric film placed at straight, before and after smooth bend are illustrated in Figure 6. The RMS voltage from piezo 3 (straight section) is higher than that of piezos 5 (before the bend) and 6 (after the bend), and the RMS voltage from piezo 6 is slightly greater than of piezo 5. The superior RMS voltage at piezo 6 compared to piezo 5 could be due to the added turbulence at the bend resulting from change in flow direction.

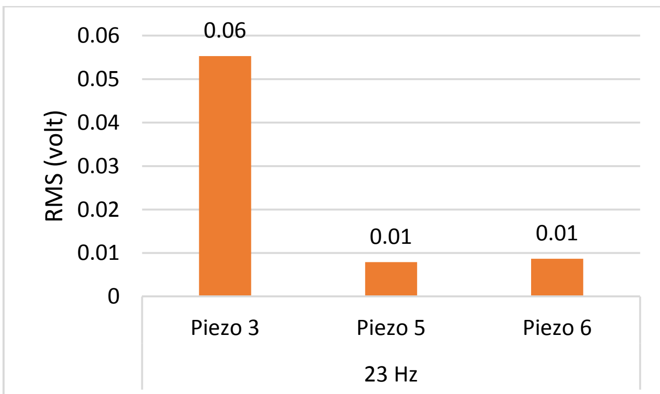

Figure 6. Comparison of RMS at straight section, before and after smooth bend

The significantly higher RMS voltage at piezo 3 is likely due to the turbulence induced by the change in vertical flow direction at the inclined pipe closer to piezo 1. Hydrodynamic entrance length is defined as 40D by (Nikuradse, 1932) for smooth pipe and 150h by (Lien et. al, 2004) for fully developed turbulent channel flow, where D is the diameter of pipe and h is the height of channel. Therefore, it is likely that piezo #3 is producing more energy than those near the bend due to the developing velocity profile in hydrodynamic entrance region caused by turbulence. In fact, the decline in RMS voltages on the straight section from piezos 1 to 2 and then to 3 can be noticed from Figure 3 as a result of this phenomenon. RMS voltage of piezo #3 is less than half of piezo #2, while that of piezo #3 is approximately $1/6^{th}$ of piezo #1. The RMS voltages of piezo #5 and #6 are significantly lower than piezo 3 as they are located much farther from the inclined pipe. This shows that the impact of possible turbulence due to inclined pipe has dissipated with distance.

Valves V1 and V3 are closed in scenarios #3 and #4 and as a result, the flow gets diverted from the 76 mm pipe to 102 mm pipe through valve V2.

Scenario 3

In this scenario, piezoelectric films labelled 3 (on straight section), 8 and 9 (before and after 90° bend respectively) are used to study the effect of sharp bend on the energy harvesting potential. The RMS values of voltage outputs from piezos 3, 8 and 9 are presented in Figure 7. The RMS voltage of piezo 9 (after bend) at 23Hz pump frequency is significantly higher than that from piezos 3 (straight) and #8 (before bend). It has been observed that more energy can be harvested from locations after the bend than prior to them because of the likely bend-induced turbulence.

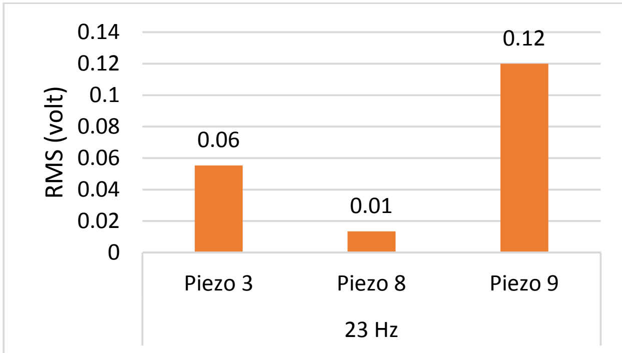

Figure 7. Comparisons of RMS at straight section, before and after 90° bend

Scenario 4

In this scenario, three piezoelectric films labelled 3 (on straight section), 4 and 7 (before and after Tee bend, respectively) as shown in Figure 1 are used to study the effect of Tee bend on the energy harvesting potential.

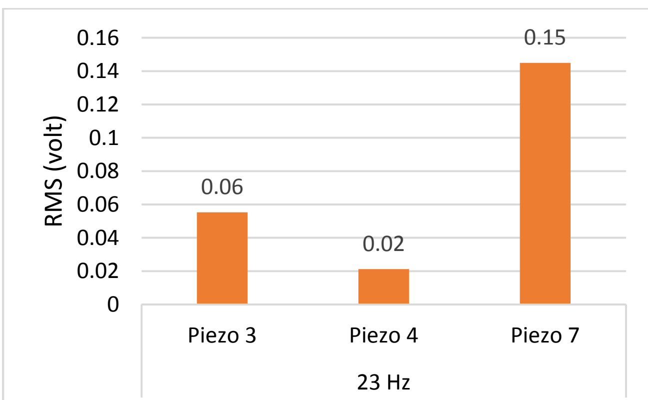

Figure 8. Comparisons of RMS at straight section, before and after Tee bend

The RMS values of voltage output from piezos 3, 4 and 7 are presented in Figure 8. The RMS voltage of piezo #7 at 23Hz pump frequency is higher than of piezo #3 and #4 because of the likely turbulence added to the flow at the Tee bend. The greater energy harvesting potential from piezo 7 could also be because of the change in pipe diameter at T2 from 76mm to 102 mm.

DISCUSSION

Table #2 presents the RMS voltages of all the piezoelectric films depicted in Figure 1. The maximum RMS voltage 0.72 volt is observed for piezo 1 at 23Hz pump frequency and the minimum 0.01 volt is observed for piezos 5, 6, 8 and 10 at 23Hz pump frequency. Piezo 1 is located very close to pump and it is possible that the RMS voltage output at this location is influenced by the added turbulence due to the pump and the inclined pipe. Piezos 7 and 9 are located after the Tee bend and 90˚ bend respectively which shows slightly higher RMS voltage (0.15 volt and 0.12 volt respectively) at 23Hz pump frequency than other locations that are not close to the pump.

Table 2: RMS voltage output of all scenarios

Piezo	Pipe Diameter	Frequency (Hz)	Flow Rate (GPM)	Tip Mass (g)	RMS (volt)
1	3 inch	23	70	12.8	0.72
		33	101	12.8	0.39
		43	135	12.8	0.46
2	3 inch	23	70	12.8	0.13
		33	101	12.8	0.08
		43	135	6.7	0.10
		43	135	12.8	0.10
		53	174	3.7	0.08
		53	174	12.8	0.09
3	3 inch	23	70	12.8	0.06
		33	101	12.8	0.03
		43	135	12.8	0.03
4	3 inch	23	70	12.8	0.02
5	3 inch	23	70	12.8	0.01
6	3 inch	23	70	12.8	0.01
7	4 inch	23	70	12.8	0.15
8	4 inch	23	70	12.8	0.01
9	4 inch	23	70	12.8	0.12
10	4 inch	23	70	12.8	0.01

The RMS voltage of piezo 7 is higher than piezo 9 because the pipe diameter increases from 3 inch to 4 inch after the Tee junction and this change could be introducing additional turbulence than just a simple 90˚ bend. According to the results presented in table 2 it could be inferred that the most potential energy harvesting locations are after the Tee bends and 90˚ bends. It is, however, possible that other locations can also produce more energy with different tip masses in order to match the resonance frequency with the natural frequency of the system.

LIMITATIONS AND FUTURE WORK

One of the limitations of this study is the lack of data on the actual natural frequency of the pipeline system and the subsequent assumption that the system frequency is equal to the pump frequency. Only RMS voltage values are presented in this study as a measure of available energy, whereas the actual available power (in watts) needs to be calculated in real time. Another limitation is focusing only on 23Hz pump frequency for most of the monitored locations. Other pump frequencies also need to be evaluated at each location in order to infer the optimal harvestable energy and the ideal locations for harvesting it for different frequencies.

CONCLUSION

Energy harvesting potential of flow-induced pipeline vibrations is investigated in this study using a two-looped pipeline test bed. The resonance frequency of the piezo is matched with that of the natural frequency of the system for maximum energy output. In this study, the maximum RMS voltage output of 0.7V and peak-to-peak output of +1V to -1V is observed at piezo 1 (23Hz). Turbulence induced by the inclined pipe closer to piezo 1 is believed to have resulted in this observed peak voltage. Additionally, RMS voltage output is higher when the resonance frequency of piezo is matched with the natural frequency of the system that is related to the pump frequency. In addition, it was observed that a smooth bend did not change the output RMS voltage significantly, but a sharp bend and a T-joint did.

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