Powering Pipeline Monitoring Sensors Using Locally Available Energy

Harshit Shukla[1]; Kalyan R. Piratla, Ph.D.[2]; Harsh Desai[3]; and Jacob Sorber, Ph.D.[4]

[1]Doctoral Student, Glenn Dept. of Civil Engineering, Clemson Univ., Clemson, SC 29634. E-mail: hshukla@clemson.edu
[2]S. E. Liles, Jr. Distinguished Associate Professor, Glenn Dept. of Civil Engineering, Clemson Univ., Clemson, SC 29634. E-mail: kpiratl@clemson.edu
[3]Doctoral Student, Electrical and Computer Engineering, Carnegie Mellon Univ., Pittsburgh, PA 15213. E-mail: harshd@andrew.cmu.edu
[4]Associate Professor, School of Computing, Clemson Univ., Clemson, SC 29634. E-mail: jsorber@clemson.edu

ABSTRACT

One of the main challenges with deploying embedded sensing systems to monitor water pipeline networks is the lack of a sustainable power source that allows the monitoring set-up to be left unattended for long periods. With the growing environmental concerns associated with batteries and the inconvenience of replacing them every once in a while, there is a great interest in developing local power sources that can support sensing and communication related power needs for monitoring water pipeline systems. With the advent of low power sensors and reliable intermittent monitoring schemes, limited availability of harvested energy may be sufficient. This paper presents an analysis of energy harvesting potential through flow-induced surface vibrations in water pipelines and a subsequent investigation into how such energy varies across the system. A systematic experimental evaluation of energy harvester on a two-looped, real-size pipeline test bed, which contains different pipe sizes, T-joints, valves, and multiple bends has been presented in this study. Piezoelectric films are attached at multiple locations on the pipeline surface to collect vibration-induced energy data. The frequency of the piezo films is matched with that of the system frequency by adding tip masses to maximize the harvestable energy. This study offers great promise to further develop and deploy long-lasting cyber monitoring systems for water pipelines.

INTRODUCTION

The water distribution systems across the world lose a significant amount (≈15 to 25%) of drinking water due to pipeline leakages (Chowdhury & Rajput, 2016; Selvakumar et al., 2013). Modern leakage detection techniques are operator-dependent, costly, and require prior information regarding the leakages to locate the precise location of the leaks in the pipeline network. Utility owners are constantly struggling to employ real-time monitoring sensors in order to assess the condition of pipeline and subsequently detect leakages in real time. Most of the water distribution network is buried, invisible, and inaccessible from the ground surface. Several researchers have developed sensor-based leakage detection techniques (Martini et al., 2017; Yazdekhasti et al., 2017), which can be used to monitor the pipeline system in real-time. The main challenge with employing these leakage detection techniques is to supply the power in the buried pipeline environment. Currently, batteries are useful power sources for such wireless sensor networks (WSN), however, they need to be replaced after their useful life which ranges from 10 days to few months depending upon the power requirements of sensors (Mohamed et al., 2011; Shukla et al., 2018; Ye & Soga, 2012). There is a growing interest among researchers to

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

© ASCE

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

develop a sustainable energy harvester, which can use locally available mechanical energy to power WSN. Many researchers focused on evaluating the energy harvesting potential using hydropower, solar (Ye & Soga, 2012), and flow-induced vibration (Pobering & Schwesinger, 2008; Shukla et al., 2018; Wang & Ko, 2010). Shinozuka et al. (2006) studied the pressure change in the water pipeline system using the MEMS-based sensor with a 30-mAh Li-Polymer battery, therefore needed direct access to change the battery over time. Stoianov et al. (2007) used sensor node systems to monitor leaks, bursts and water quality in sewer and water distribution network. They used batteries to power the sensor node system with minimum data transmission; however, batteries only lasted 50-62 days and needed replacement periodically. Pobering & Schwesinger (2008) developed energy harvester using cantilever piezoelectric film, which was tested in a wind channel to produce energy due to airflow. Wang & Ko (2010) created a device with flexible diaphragm and pressure chamber to enhance the flow induced vibration for small diameter pipes. The energy harvesters developed by these researchers is less reliable as the available energy is uncertain and it varies with flow and time. Ye & Soga (2012) reported that in order to record data every fifteen minutes and transmit it to local control center every thirty minutes, tens of milliwatts (mW) of power was required. Shukla et al. (2018) used piezoelectric film to harvest energy from flow-induced surface vibration and concluded there is a small amount of energy available that can be used to power small sensor networks. Limitations of this study were the lack of actual natural frequency estimation of a pipeline network for different flow conditions and use of only one pump frequency to study the available harvestable energy. Yazdekhasti et al. (2017) developed a vibration-based leakage detection index (LDI) method to detect leakages in the water pipeline system. Shukla et al. (2018) reported that a standard sensor system comprising of an accelerometer (ADXL362) and a microcontroller (MSP430FR5969), would require about 1.8V power each to record acceleration signal used in LDI method.

In this paper, flow-induced surface vibration was used to evaluate the energy harvesting potential through piezoelectric films mounted on the water pipeline network with the help of a clamping kit. This paper addresses the limitations of Shukla et al. (2018) by evaluating energy harvesting potential through matching the natural frequency of the system with the resonance frequency of piezoelectric film and studying multiple pump frequencies to maximize the harvestable energy. The objectives of this study were to determine (a) how different pump frequencies affect the harvestable energy and (b) how the energy harvesting potential varies with pipeline bedding conditions.

METHODOLOGY

This study uses a two-looped PVC pipeline network, which consists of Dayton 3KV80A pump connected to an 820-litre reservoir, multiple T-joints, valves, bends, varying pipe diameters and burial conditions to study the energy harvesting potential of flow-induced surface vibration. Figure 1 shows the schematic layout of the experimental setup used in this study. The loop connecting the pump with reservoir depicted as a solid line is 3-inch (76 mm) diameter pipeline and dotted lines show the 4-inch (102 mm) diameter pipeline in Figure 1. This pipeline network is placed over sand-cushion bedding at an average depth of 0.6 m from the ground surface. To measure the flow rate in this network FMG3002-PP-D type magnetic flowmeter was installed on 3-inch (76 mm) diameter pipeline.

In this study, flow-induced surface vibration was used as a source of mechanical energy to harvest electrical energy by using the direct piezoelectric effect. Piezoelectricity is generated by any piezoelectric material when it is subjected to any mechanical stress by compressing or

© ASCE

squeezing. To capture the available ambient energy a MIDE PPA 1021 type piezoelectric film along with PPA 9001 type clamping kit was attached on various locations across the pipeline network. PPA 1021 was used in this study because it is designed to work with low-frequency vibration with 0.25g to 1g acceleration range. Clamping kit PPA 9001 allows altering the resonance frequency of the piezoelectric film by changing the tip mass at different clamping positions. A 16-channel Saleae logic analyzer was connected to the piezoelectric films to record the voltage output. Saleae logic analyzer has the inbuilt 12-bit analog to digital converter (ADC) for every channel and it can measure the signals in the range -10V to 10V form all 16 channels simultaneously. ADC allows it to convert the incoming analog signals to a digital value and record the data. The sampling frequency of Saleae ranges between 10Hz and 50MHz and its digital output range starts from 0 (digital) for -10V (analog) to 4095 (digital) for +10V (analog) (Shukla et al., 2018). The resolution of this device is 4.88mV/LSB, which indicates that for every 4.88mV increment in analog signal the digital output will increase by one unit (Shukla et al., 2018).

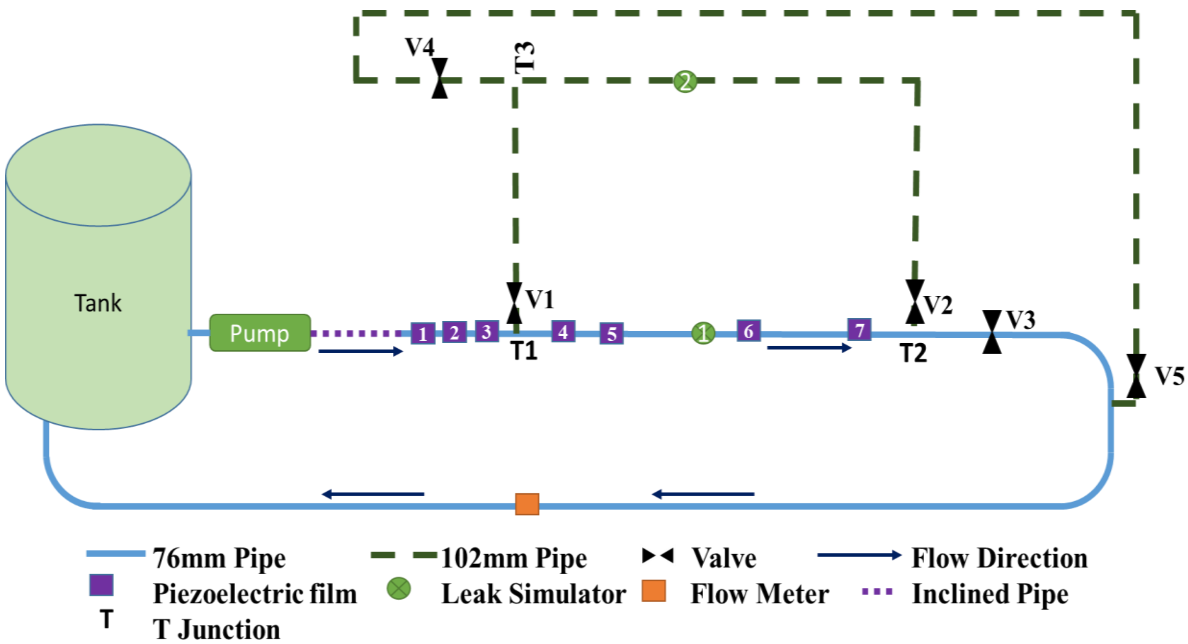

Figure 1: Schematic layout of the experimental setup used in this study.

The harvestable energy output is maximum when the resonance frequency of the piezoelectric film is matched with the natural frequency of the system (source of vibration) because the power density and piezoelectric efficiency responsible for energy harvesting both are frequency dependent (Li et al., 2014). The resonance frequency of piezo PPA 1021 is 60Hz with 1.7-gram tip mass and 23Hz with 12.7-gram tip mass (MIDE, 2017). The tip mass for different frequencies can be calculated using Eq. 1 (MIDE, 2017):

$$m_t = \frac{k}{(2\pi f)^2} - m \tag{1}$$

where m_t is the required tip mass for given frequency f, k is the effective stiffness and m is the effective mass of the piezoelectric film. The pump used in this study has a frequency range of 0Hz to 60 Hz to regulate the flow conditions in the pipeline system. Shukla et al., (2018) assumed that the natural frequency of the pipeline system is same as the pump frequency;

© ASCE

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

however, in this study, multiple frequencies were observed at which the pipeline was vibrating. Six Bruel and Kjaer 4507-B-006 type accelerometers were mounted at different locations to record the acceleration signal of pipeline for varying flow conditions. In order to determine the natural frequency of pipeline system, Fast Fourier transform (FFT) was calculated after applying appropriate filters for each acceleration signal. FFT plots showed that there were multiple peaks at different frequency levels which indicates that there were more than one natural frequencies for any given flow condition. Therefore, multiple natural frequencies of the pipeline system were selected for any given flow condition and tip masses of the piezoelectric film were changed accordingly to match the resonance frequency with the dominant natural frequency.

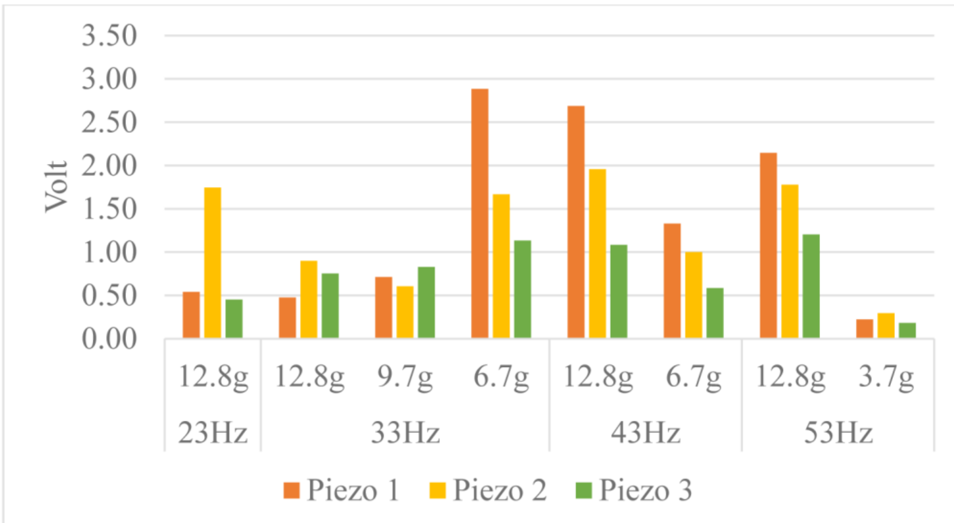

Figure 2: RMS voltage output of scenario 1.

RESULTS AND DISCUSSION

Shukla et al., (2018) reported that a small amount of energy could be harvested by flow-induced surface vibration. This study used the same experimental setup to explore the energy harvesting potential by modifying the pipeline setup configuration. In this study, the 3-inch pipeline was not placed over a sand cushion at the time of experiment instead; sand bedding was removed beneath the 3-inch pipeline and it was supported by ground near T-joints making it a simply supported beam to study the effect of additional vibration on harvestable energy. After removing the sand bed, the piezoelectric films were attached at different locations to determine the harvestable energy. Four scenarios were created to find out the critical location for energy harvesting across the pipeline network. Ten sets of 15-second data were recorded for all piezoelectric films of each scenario with a sampling frequency of 500 Hz to avoid any statistical or human errors. These datasets were recorded from multiple locations simultaneously when the flowmeter readings became constant indicating a steady state condition.

Scenario 1

In this scenario valve V1, V2 and V5 were closed to allow the flow only in 3-inch pipeline loop. Three piezoelectric films (1, 2, 3) were mounted at locations labeled #1, #2, and #3 in Figure 1 respectively to investigate the available harvestable energy after inclined pipe.

The Root Mean Square (RMS) voltages of these piezoelectric films were calculated at four

© ASCE

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

pump frequencies (23Hz, 33Hz, 43Hz, and 53Hz) with varying tip masses to alter the resonance frequency of the piezo as shown in Figure 2. It can be seen from Figure 2 that the RMS voltages for 33 Hz pump frequency with 6.7-gram tip mass of all three piezoelectric films are very high compared to other tip masses. Similarly, in the case of 43 Hz and 53 Hz pump frequencies the 12.8-gram tip mass generates higher RMS voltage compared to other tip masses. Shukla et al., (2018) reported that the inclined pipe enhances the turbulence in the straight 3-inch pipe and the maximum RMS voltage output recorded was 0.7V near the inclined pipe. However, in this study, the maximum RMS voltage was 2.8V near the inclined pipe. This change in the RMS voltage is due to the added turbulence in the system by making it a simply supported beam or in other words, by removing the bedding and allowing it to vibrate freely.

Scenario 2

In this scenario, three piezoelectric films (1, 2, and 3) were mounted at locations labeled #2, #4, and #5 in Figure 1 respectively to investigate the available harvestable energy. The system configuration of this scenario was the same as scenario 1. The objective of this scenario was to study the impact of inclined pipe on flow-induced surface vibration and subsequently on harvestable energy.The RMS voltages of these piezoelectric films were also calculated at four pump frequencies (23Hz, 33Hz, 43Hz, and 53Hz) with varying tip masses as shown in Figure 3. It can be noted from Figure 3 that the RMS voltage of piezo 3 is less than piezo 1 for most of the pump frequencies and tip masses. This reduction in RMS voltage indicates that the turbulence added by the inclined pipe dissipates with the distance. The RMS voltage of piezo 2 and 3 for pump frequency 43 Hz and 53Hz with 12.8-gram tip mass is more than 1V. At the same locations with similar pump frequency, Shukla et al. (2018) reported significantly less RMS voltage output. The change in RMS output is because the soil bedding was removed in this study.

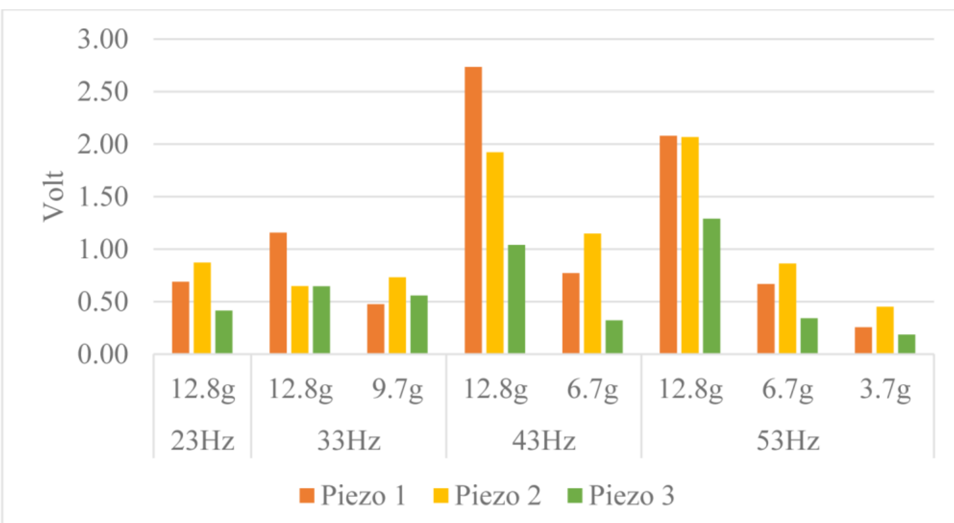

Figure 3: RMS voltage output of scenario 2.

Scenario 3

In this scenario three piezoelectric films (1, 2, and 3) were mounted at locations labeled #5, #6, and #7 in Figure 1 respectively to investigate the available harvestable energy on a straight section. The system configuration of this scenario was the same as scenario 1. The RMS voltage

© ASCE

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

outputs of these piezoelectric films were calculated in a similar manner as scenario 1 and 2 as shown in Figure 4. It can be seen from Figure 4 that the RMS voltage output of piezo 1 which was mounted in location #5 (see Figure 1) for 23 Hz, 43 Hz, and 53 Hz with 12.8-gram tip mass is approximately 2V. For similar system configuration in scenario 2, at location #5 the RMS voltage output is approximately 0.5V. This change in the RMS output could be due to the multiple natural frequencies of the pipeline system. The dominant natural frequency for the same flow condition may vary with time and space, which resulted in the higher RMS output in scenario 3 compared to scenario 2. This is one of the major challenges to developing a sustainable energy harvester using flow-induced surface vibration because the resonance frequency of the MIDE piezoelectric film cannot be changed automatically according to the varying dominant natural frequency of the system. It must be noted that the RMS voltage of piezoelectric film 3 (at location #7 as shown in Figure 1) was found more than 1V for 53 Hz pump frequency with 12.8-gram tip mass. 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 the pipe and h is the height of the channel. All three piezoelectric films were mounted in the proximity of hydrodynamic entrance length and resulted in higher RMS voltage output due to the added turbulence by the inclined pipe.

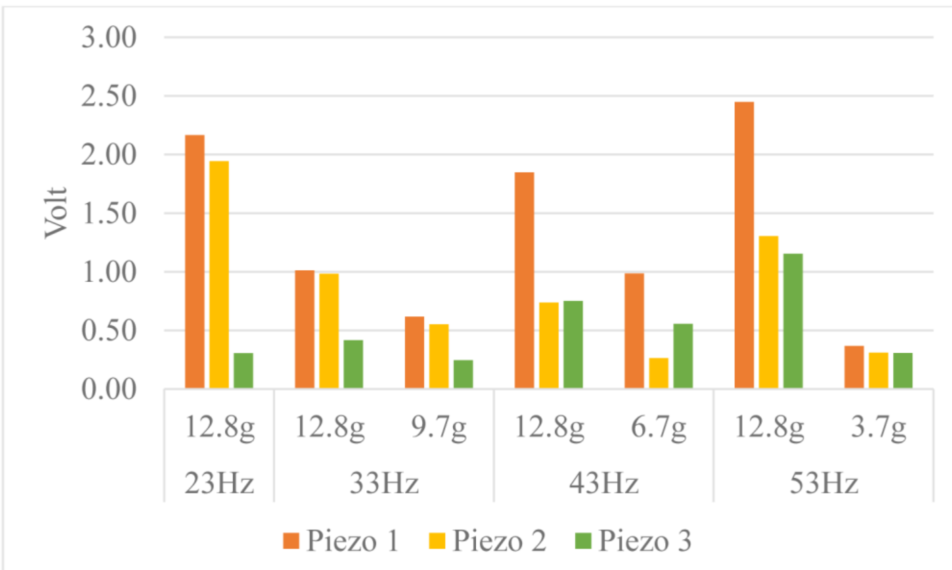

Figure 4: RMS voltage output of scenario 3.

Scenario 4

In this scenario, only one piezoelectric film was mounted at location #2 as shown in Figure 1. The objective of this scenario was to calculate the power in watts generated by the piezoelectric film. In order to calculate the power, the Ekho device designed and developed by Hester et al., (2014) was connected to the piezoelectric film. The piezoelectric films generate alternative current (AC) and most of the monitoring sensors such as ADXL362 type accelerometer and MSP430FR5969 type microcontroller require direct current (DC) to record data. Therefore, a low power AC to DC converter was also connected between EKho device and piezoelectric film. Figure 5 shows the RMS voltage output of piezo attached on the pipeline for different pump frequencies and tip masses. It can be seen from Figure 5 that the RMS voltage at 53Hz pump

© ASCE

frequency with 16-gram tip mass was maximum; therefore, Ekho device along with the AC to DC converter and filter was connected with piezo at this pump frequency. Figure 6 shows the power output in watts for piezoelectric film attached on the 3-inch pipeline.

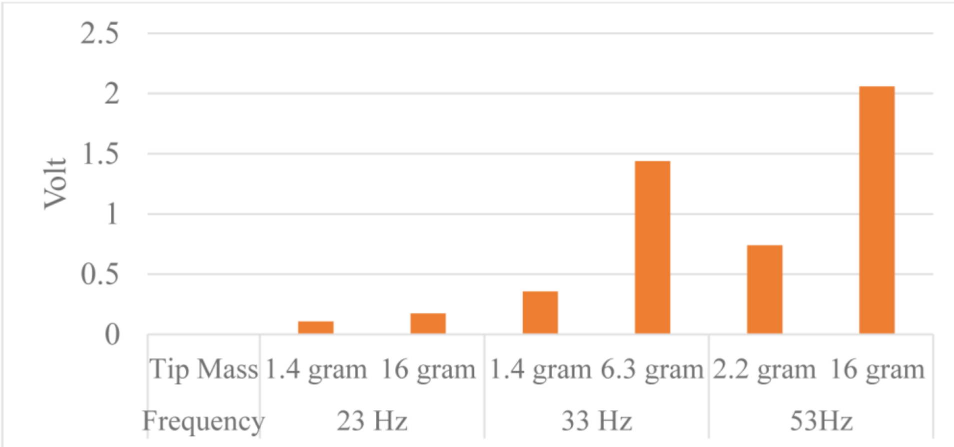

Figure *5*: RMS voltage output of scenario 4.

It can be noted that the available power was in the range of 2 to 4 µW (microwatts) with few peaks showing more than 10 µW power. Ekho device is specially designed for such low power generation and to use it for pipeline energy harvesting it is required to change the AC output of piezo to DC using some filters and rectifiers, which need to be powered through the energy generated by a piezo on-site.

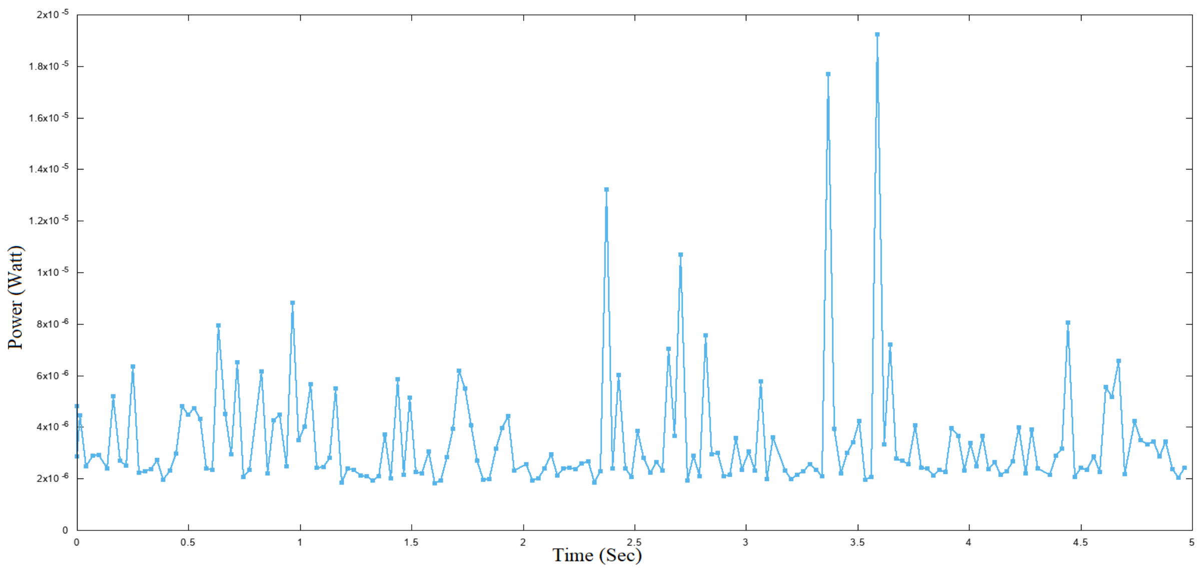

Figure *6*: power output in watts for piezoelectric film attached on the 3-inch pipeline.

Sadeghioon et al., (2014) reported that ultra-low power smart wireless sensor network could be operated at 2µW with careful selection of hardware and firmware. Commercially available sensors such as ADXL362 (accelerometer) coupled with MSP430FR5969 (microcontroller) require 1.8V each to record the acceleration signal (Shukla et al., 2018). Additional power is required to transmit the data from microcontroller to the local server located above ground or to

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

the cloud-based server. Power consumptions also varies with the sampling frequency and rate of transmission(Mencarelli et al., 2012). WaterWise (a sensor to measure the pressure and flow rate) requires 4.5-6mW power for continuous monitoring(Mencarelli et al., 2012; Whittle et al., 2010). Similarly, Pipenet sensor, which could measure the pressure and pH with sampling frequency of 100 Hz for 5-second data every 5 minutes, requires 10mW power(Mencarelli et al., 2012; Stoianov et al., 2007). The power generated by energy harvester in this study needs to be converted from alternative current (AC) to direct current (DC) in order to power any monitoring sensors. The total energy generated by a single piezo appears to be insufficient to power the filter, rectifier and the Ekho device. However, the results shown in this study are promising and require further research to support development of a sustainable energy harvester that can be used to power real-time monitoring sensors in the buried pipeline environment using low power consumption sensors with higher accuracy.

CONCLUSION

Energy harvesting potential of flow-induced surface vibration of a pipeline network was evaluated in this study by using the MIDE PPA 1021 piezoelectric film. The flow conditions were regulated by the pump installed in the pipeline network to study the impact of varying flow conditions at multiple locations across the pipeline network. Multiple dominant natural frequencies of the pipeline system were found in this study and as a result, different tip masses were used to alter the resonance frequency of the piezoelectric film to maximize the harvestable energy. In this study, the maximum RMS voltage of 2.8V was observed at location #1 when the pump frequency was 43 Hz. Turbulence induced by the inclined pipe closer to location #1 is believed to have resulted in this observed high voltage. The RMS voltage outputs for all locations were found close to 1V for at least one tip mass and pump frequency combination in all scenarios tested in this study.

The first objective of this study was to evaluate the energy harvesting potential with varying pump frequencies. RMS voltage output does vary with the pump frequencies and it was observed that the flow-induced vibration contains multiple dominant frequencies. Therefore, it would be difficult to conclude that one particular pump frequency generates higher RMS voltage. The dominant natural frequency of the pipeline system at any operating pump frequency needs to be matched with the resonance frequency of piezoelectric film for maximum power generation. The second objective was to determine the effects of pipeline bedding condition. It was found that the pipe sections, which were not supported by the soil bed (acting like a simply supported beam), seem to have more vibration and generate higher RMS voltage compared to the pipe section placed over soil bed.

The limitations of this study were (a) only a small section of the two-looped pipeline network was used for energy harvesting evaluation, (b) unavailability of low power AC to DC converter and rectifiers, and (c) unable to match the resonance frequency of the piezoelectric film with the dominant natural frequency of the pipeline system because the dominant frequency varies with time and space. The results presented in this study are promising and should be pursued on a larger scale to develop a sustainable energy harvesting solution for real-time monitoring of water pipeline systems.

ACKNOWLEDGMENT

This research was supported by the National Science Foundation (NSF) under Grant No. 1539536. The results and conclusion presented in this paper are those of the authors and should

© ASCE

not be interpreted as necessarily representing the official policies, either expressed or implied, of the United States Government. The authors are very grateful to the NSF for this support.

REFERENCES

Chowdhury, R. K., & Rajput, M. A. (2016). Leakage and failures of water distribution mains in the city of Al Ain, UAE. *Water Practice and Technology*, *11*(4), 806. https://doi.org/10.2166/wpt.2016.086

Hester, J., Scott, T., & Sorber, J. (2014). Ekho: realistic and repeatable experimentation for tiny energy-harvesting sensors. In *Proceedings of the 12th ACM Conference on Embedded Network Sensor Systems - SenSys '14* (pp. 1–15). New York, New York, USA: ACM Press. https://doi.org/10.1145/2668332.2668336

Li, H., Tian, C., & Deng, Z. D. (2014). Energy harvesting from low frequency applications using piezoelectric materials. *Applied Physics Reviews*, *1*(4), 041301. https://doi.org/10.1063/1.4900845

Lien, K., Monty, J. P., Chong, M. S., & Ooi, A. (2004). The Entrance Length for Fully Developed Turbulent Channel Flow. In *15th Australasian Fluid Mechanics Conference*. Sydney, Australia: The University of Sydney. Retrieved from https://pdfs.semanticscholar.org/d5c4/d33ca32427be16a566fdd24435b53138f8b7.pdf

Martini, A., Troncossi, M., & Rivola, A. (2017). Leak Detection in Water-Filled Small-Diameter Polyethylene Pipes by Means of Acoustic Emission Measurements. *Applied Sciences*, *7*(1). https://doi.org/10.3390/app7010002

Mencarelli, M., Pizzichini, M., Gabrielli, L., Spinsante, S., & Squartini, S. (2012). Self-Powered Sensor Networks for Water Grids : Challenges and Preliminary Evaluations. *Multidisciplinary Journals in Science and Technology, Journal of Selected Areas in Telecommunications (JSAT), October*, 1–8. Retrieved from https://pdfs.semanticscholar.org/8cc6/0149a88b993f23c6937402d5051d1a910508.pdf

MIDE. (2017). *PPA PRODUCTS Datasheet & User Manual*. Medford MA. Retrieved from https://info.mide.com/hubfs/ppa-piezo-product-datasheet.pdf

Mohamed, M. I., Wu, W. Y., & Moniri, M. (2011). Power harvesting for smart sensor networks in monitoring water distribution system. In *2011 International Conference on Networking, Sensing and Control* (pp. 393–398). IEEE. https://doi.org/10.1109/ICNSC.2011.5874897

Nikuradse, J. (1932). Gesetzmäßigkeiten der turbulenten Strömung in glatten Rohren : mit 9 Zahlentafeln. *Forschungsheft / Verein Deutscher Ingenieure*. Retrieved from https://www.tib.eu/en/search/id/TIBKAT%3A186532822/Gesetzmäßigkeiten-der-turbulenten-Strömung-in-glatten/

Pobering, S., & Schwesinger, N. (2008). Power supply for wireless sensor systems. *Proceedings of IEEE Sensors*, 685–688. https://doi.org/10.1109/ICSENS.2008.4716534

Sadeghioon, A. M., Metje, N., Chapman, D. N., & Anthony, C. J. (2014). SmartPipes: smart wireless sensor networks for leak detection in water pipelines. *Journal of Sensor and Actuator Networks*, *3*(1), 64–78.

Selvakumar, A., Morrison, R., Sangster, T., Downey, D., Matthews, J., & Condit, W. (2013). State of Technology for Rehabilitation of Water Distribution Systems.

Shinozuka, M., Park, C., Chou, P. H., & Fukuda, Y. (2006). Real-time damage localization by means of MEMS sensors and use of wireless data transmission. In A. A. Diaz, H. F. Wu, S. R. Doctor, & Y. Bar-Cohen (Eds.) (Vol. 6178, p. 61780A). International Society for Optics and Photonics. https://doi.org/10.1117/12.659084

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

© ASCE

Shukla, H., Desai, H., Sorber, J., & Piratla, K. R. (2018). Evaluation of Energy Harvesting Potential in Water Pipelines to Power Sustainable Monitoring Systems. In *Construction Research Congress 2018* (pp. 465–475). New Orleans, Louisiana: American Society of Civil Engineers. https://doi.org/10.1061/9780784481295.047

Stoianov, I., Nachman, L., Madden, S., & Tokmouline, T. (2007). PIPENETa wireless sensor network for pipeline monitoring. In *Proceedings of the 6th international conference on Information processing in sensor networks - IPSN '07* (p. 264). New York, New York, USA: ACM Press. https://doi.org/10.1145/1236360.1236396

Wang, D.-A., & Ko, H.-H. (2010). Piezoelectric energy harvesting from flow-induced vibration. *Journal of Micromechanics and Microengineering*, *20*(2), 25019. Retrieved from http://stacks.iop.org/0960-1317/20/i=2/a=025019

Whittle, A. J., Girod, L., Preis, A., Allen, M., Lim, H. B., Srirangarajan, S., Fu, C., Wang, K. J., & Goldsmith, D. (2010). WATERWISE@SG: A testbed for continuous monitoring of the water distribution system in Singapore. In *Water Distribution System Analysis 2010*. Tucson, AZ, USA: WDSA2010. Retrieved from https://pdfs.semanticscholar.org/3aec/bf40552b13ce056ba0fb0f1d6858692071e5.pdf

Yazdekhasti, S., Piratla, K. R., Atamturktur, S., & Khan, A. A. (2017). Novel vibration-based technique for detecting water pipeline leakage. *Structure and Infrastructure Engineering*, *13*(6), 731–742. https://doi.org/10.1080/15732479.2016.1188318

Ye, G., & Soga, K. (2012). Energy Harvesting from Water Distribution Systems. *Journal of Energy Engineering*, *138*, 7–17. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000057

Downloaded from ascelibrary.org by Carnegie Mellon University on 12/17/24. Copyright ASCE. For personal use only; all rights reserved.

© ASCE