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Simulation of Piezoelectric Transducer for Detecting Water Leak in Polyethylene Pipelines

Ahmad Adzim Mohd Puad[1], Siti Zarina Mohd Muji[1*], Nuriffat Roslee[1], Herdawatie Abdul Kadir[1], Khalid Isa[1], Ariffuddin Joret[1], Nuramin Fitri Aminuddin[1]

[1]Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA

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Abstract: Pipeline leakage is known to cause severe economic losses and environmental harms. Conventionally, the pipeline monitoring methods, such as investigation (visual), GPR, or correlation have slow leakage responses and require a large human workforce. The objective of this work is to implement piezoelectric sensors for detecting pipeline leakage response by using acoustic pressure and sound pressure principles. Two types of pipe with diameter 50mm were used in the work, namely polyethylene pipe with and without aluminium coating. In this project, the bubble is used as the leakage indicator where several pipes with diameters of 30mm, 20 mm and 10 mm are used to mimic the bubble. A piezoelectric transmitter is then used to produce sound waves and allowing the shear waves to propagate throughout the pipeline vessel. A receiver piezoelectric then converts the motion of shear waves into electrical signals. The shear waves obtained seen to resulted within three values of frequencies, which are 3 kHz, 6 kHz, and 9 kHz. The obtained results are then analyzed using the COMSOL Multiphysics™ software installed on the computer. From the findings, it can be concluded that the acoustic pressure field is affected by the size of the bubble and the appearing water bubbles in the pipe can be used to detect the leakage. It also comfirms that the polyethylene pipe with aluminium coating is more suitable to be used along with a piezoelectric transducer compared to polyethylene pipe without aluminium coating.

Keywords: Pipe Leakage, Piezoelectric, COMSOL Multiphysics™

1. Introduction

Water is an important source for human and environmental resources for daily use, agricultural and industrial activities. Owing to the high quality of living and advanced technologies, the need for water has risen over the years. Since 1950, global water production has tripled due to urban development [1].

Water crisis cases in Selangor state is the highest in Malaysia. The first water crisis case was announced in Selangor in 2007 due to a large leakage pipeline. The explanation for this is that the distribution pipes are old and under heavy strains from the water supply capacities that could be

*Corresponding author: szarina@uthm.edu.my

channelled into their initial design [2]. Development practises and heavy vehicle operations have also led to the leaking of pipes. On the basis of a visit to the Selangor Water Center Sdn Bhd on 17 September 2019, a range of methods was used by Selangor Water Protection to track leakage of water pipes. One of the methods for detecting pipe leaks is to inspect (visually) if there was water leakage. If a water leakage region has been detected, the leakage correlator and the ground-breaking radar (GPR) approaches are then used to identify the site of the water leak at the pipelines, before the troubleshooting process takes place [3]. However, these approaches require a large human workforce. This work is conducted to resolve the workforce issue by replacing both approaches with a piezoelectric sensor to detect a water pipe leakage. With the use of water bubbles that appeared in the pipe leakage, the signals transmitted by a piezoelectric transmitter will be blocked by the bubbles, and the strength of the receiving signal will become weak. This could be an indicator of pipe leakage.

1.1 Polyethylene characteristics

In industry, polyethylene pipelines have been readily exposed to a number of damages due to manufacturing defects and incorrect installations [4]. The pipelines are the most commonly used for delivering filtered water to home and transferring raw waste to treatment plants before the cast iron or vitrified clay pipes. Currently, all modern pipe installations consist of polyethylene pipes must comply with ASTM D1784 [5]. Erosion or cracking damage to piping can lead to catastrophic failures. Pipes and other materials used in the fracturing process are of special concern, where the working pressure of the pipe can be measured as high as 15000 psi and localised corrosion is caused by particulate matter trapped in the fracturing fluid [6].

1.2 Piezoelectric sensor

A piezoelectric sensor is a device that uses a piezoelectric effect to determine the force or pressure by converting it to an electrical charge. In the year 1880, Jacques Curie discovered the sensor and started to use the piezoelectric effect in the manufacturing field in the year 1950. He also introduces the relationship between piezoelectric, and crystalline structure [7]. Some characteristics of the piezoelectric sensor are that it has a high Direct Current (DC) impedance and its voltage at the source is directly proportional to the stress, pressure or force applied [8]. Gautschi makes the comparison characteristics of the piezoelectric sensor in Table 1 [9].

Table 1: Characteristics of piezoelectric sensor

Principle	Strain Sensitivity **[V/με]**	Threshold **[με]**	Span to Threshold Ratio
Piezoelectric	5.0	0.00001	100,000,000
Piezoresistive	0.0001	0.0001	2,500,000
Inductive	0.001	0.0005	2,000,000
Capacitive	0.005	0.0001	750,000
Resistive	0.000005	0.01	50,000

Bareille had designed a system to generate and receive torsion-guided waves using piezoelectric-transducers [10]. The piezoelectric receiver detects the reflections and converts the waves to electrical signals. The force between the piezoelectric and the pipe is applied to ensure good coupling. The transmission of the signal sweeps several frequencies obtained at the piezoelectric receiver. These signals also depend on pipe conditions. In order to ensure the generation of the specified signals, the size of the piezoelectric line must be sufficient to fit the size of the pipe. The number of piezoelectric sensors needed to be used can be determined from the number of piezoelectric shear properties available in the structures. Lowe et al affirm the incidence of piezoelectric patches to pipe size [11].

2. Methodology

Figure 1 displays the project block diagram comprising a piezoelectric sensor (transmitter and receiver) and a polyethylene pipeline built-in 2D using the COMSOL Multiphysics™ software. The signal frequencies obtained from the piezoelectric receiver sometimes are affected by the test object materials.

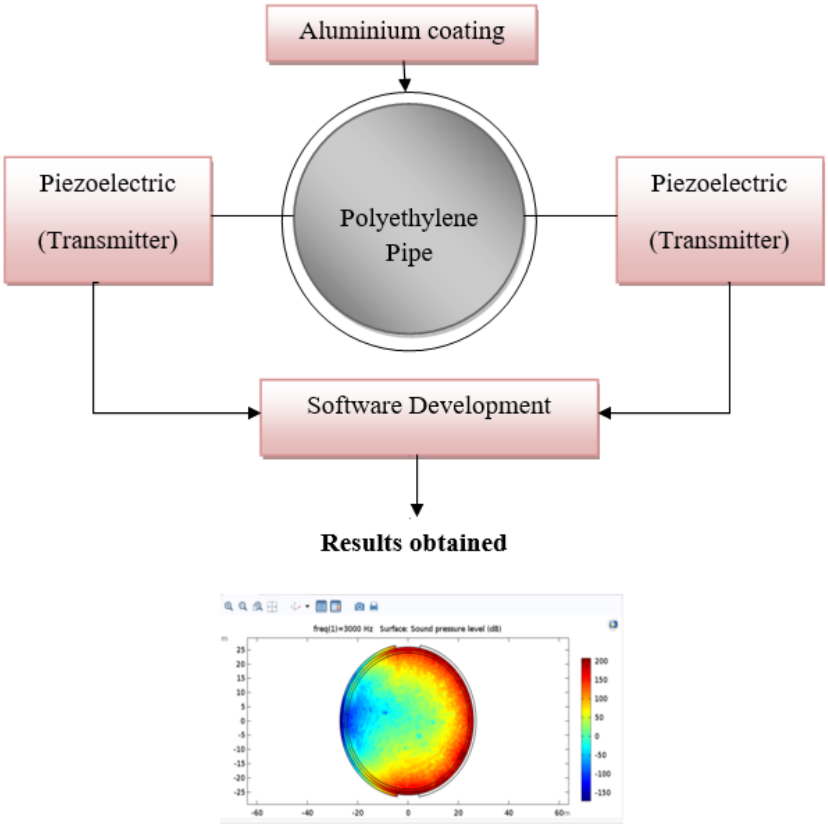

Figure 1: Project block diagram

This system incorporates a piezoelectric sensor to generate sound waves for vibration, which causes the shear wave to be distributed throughout the pipe in order to measure the state of the water. Two piezoelectric sensors were used in this experiment, the first is a piezoelectric transmitter to produce sound waves and allowing the shear waves to propagate throughout the pipeline vessel. The second is a receiver piezoelectric to convert the motion of shear waves into electrical signals. The signals are then analyzed from COMSOL Multiphysics™ software installed on the computer. Two types of pipe, namely polyethylene pipe with and without aluminium coating (shown in Figure 2 and Figure 3) with diameter of 50 mm were used in this work.

Figure 2 and Figure 3 demonstrate the configuration of the polyethylene pipe with or without a coating to be measured in 2D with 50 mm diameter sizes to determine the flow of water. Piezoelectric sensors shall be mounted outside the pipes where the shear waves propagating in the pipe are collected.

3. Results and Discussion

The shear waves collected seen to result within three values of signal frequencies, which are 3 kHz, 6 kHz, and 9 kHz in the experiment. These sheer waves rely on the acoustic effects of the piezoelectric receiver produced by the piezoelectric transmitter in water. The distance between the transmitter and receiver piezoelectric in this test is 50 mm, as seen in Figure 4. The resulted signal frequencies are then analyzed using the COMSOL Multiphysics™ software installed on the computer.

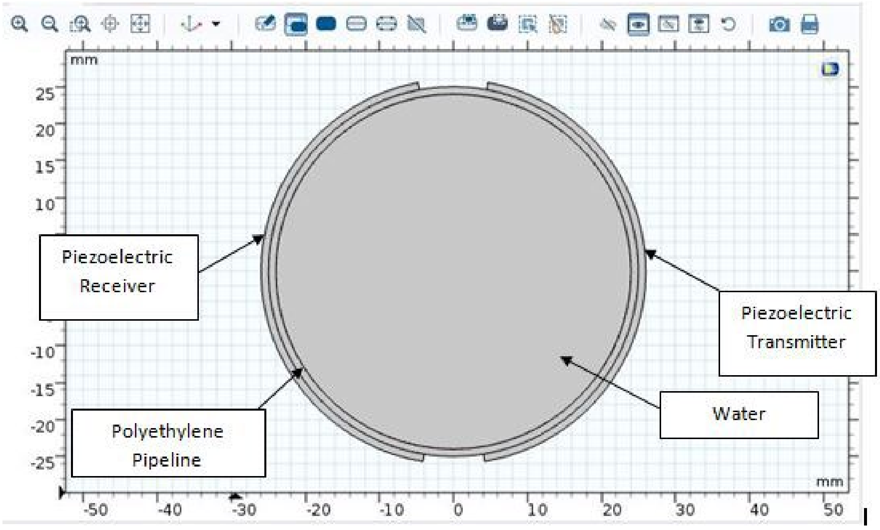

Figure 2: Polyethylene pipe without aluminium coating

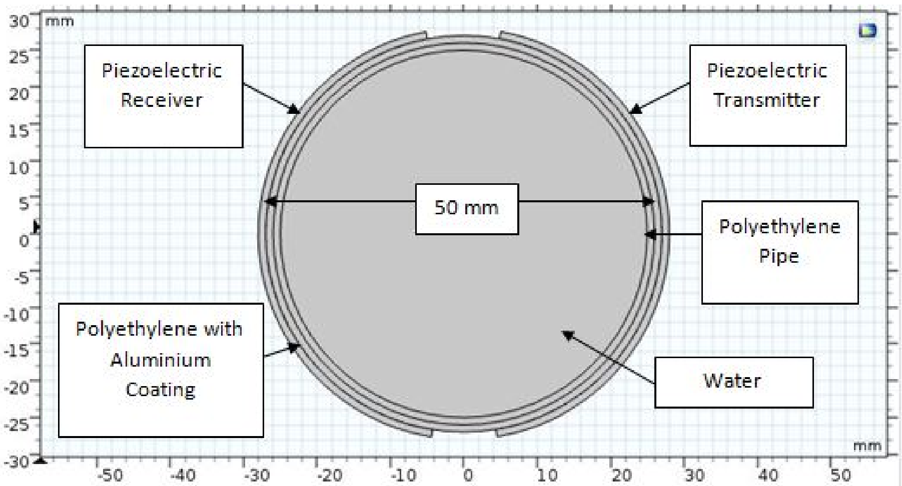

Figure 3: Polyethylene pipe with aluminium coating

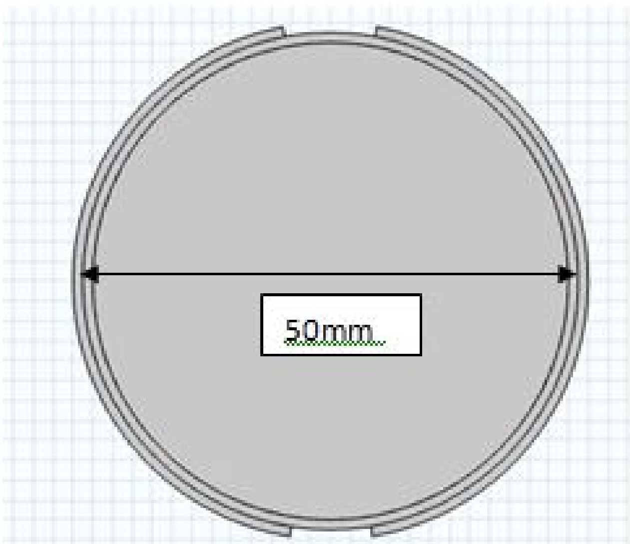

Figure 4: Distance between transmitter and receiver on the polyethylene pipe

3.1 Acoustic pressure analysis for normal pipe

Table 2 shows distinct signal frequency values with total acoustic pressure in Pascal (Pa) using the boundary probe 1. The graph is then plotted on the basis of Table 2, as seen in Figure 5.

Table 2: Total value acoustic pressure in the normal pipe

Frequency, *f* (kHz)	Total Acoustic Pressure Field (Pa), Boundary Probe 1	
	Polyethylene Pipe	Polyethylene with Aluminium Coating
3	-0.72446	25.136
6	-0.72616	0.38715
9	-0.74233	0.00185512

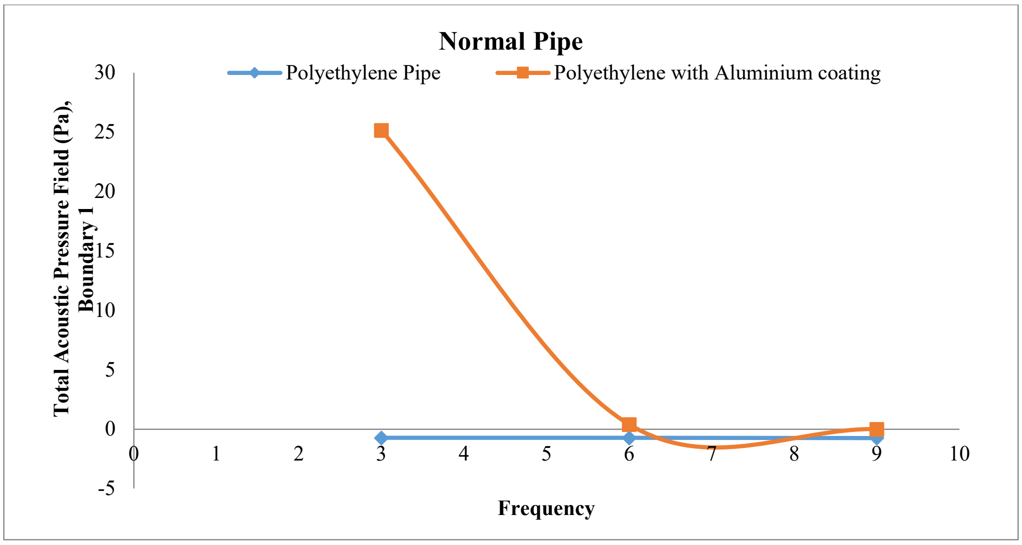

Figure 5: Graph of acoustic pressure analysis in normal pipe

From Figure 5, it can be indicated that the graph of acoustic pressure decrease when the frequency increase in polyethylene with aluminium coating, and remained constant in polyethylene pipe.

3.2 Acoustic pressure analysis for leakage pipe

Table 3 to Table 5 depict the acoustic pressure value with differing frequency and diameter of the spherical pipes. Owing to the scale of the water leakage inside the pipe, the overall acoustic pressure field is modified accordingly. The size of the water bubble appeared in pipe leakage determines the output signal on the piezoelectric receiver.

Table 3: Acoustic pressure value with frequency of 3 kHz

Diameter of Bubble Size (mm)	Total Acoustic Pressure Field (Pa), Boundary Probe 1 With Frequency 3 kHz	
	Polyethylene Pipe	Polyethylene with Aluminium Coating
30	-0.12932	0.003616
20	0.34657	-0.13007
10	-0.028918	-0.010656

The graph based on Table 3 shown in Figure 6 reveals the acoustic pressure increased by 20 mm in bubble size diameter (0.34657) in polyethylene pipe and decreased (-0.13007) in polyethylene with aluminium coating.

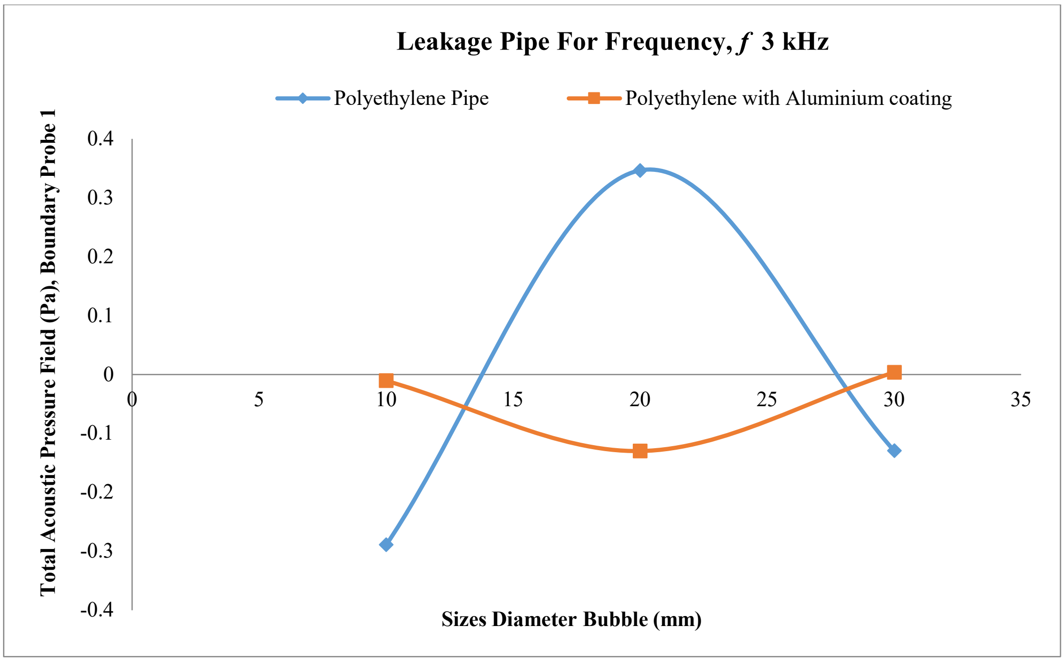

Figure 6: Graph acoustic pressure analysis with frequency, *f* 3 kHz

In Table 4, at the polyethylene pipe, the acoustic pressure decreases and declines marginally at the level of the 30 mm bubble while for polyethylene with aluminium coating it shows the nonlinear relation but shows highest value at 30 mm bubble.

Table 4: Acoustic pressure value with frequency of 6 kHz

Diameter of Bubble Size (mm)	Total Acoustic Pressure Field (Pa), Boundary Probe 1 With Frequency 6 kHz	
	Polyethylene Pipe	Polyethylene with Aluminium Coating
30	-0.25586	0.0036160
20	-0.25166	0.0035718
10	-0.25124	0.0035862

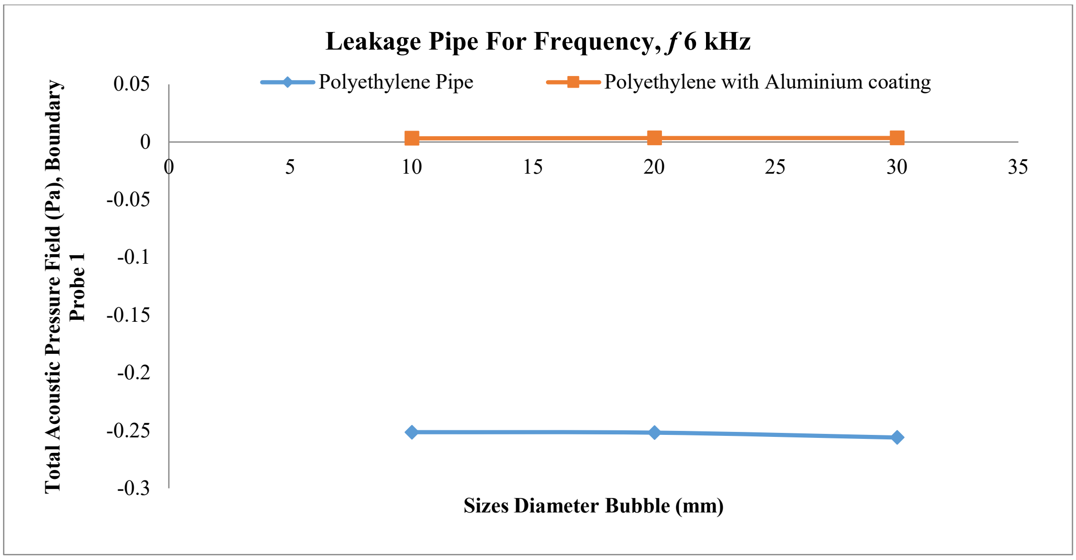

Figure 7: Graph acoustic pressure analysis with frequency, *f* 6 kHz

Table 5 and Figure 8 display a steady rise in acoustic pressure as the diameter of the polyethylene with aluminium coating increases. In the case of polyethylene pipe, the acoustic pressure decreased starting from a diameter bubble of 10mm.

Table 5: The value acoustic pressure with frequency, *f* 9 kHz

Diameter of Bubble Size (mm)	Total Acoustic Pressure Field (Pa), Boundary Probe 1 With Frequency 9 kHz	
	Polyethylene Pipe	Polyethylene with Aluminium Coating
30	-0.042968	1.3024
20	-0.042911	-1.30E-06
10	-0.042887	-1.30E-06

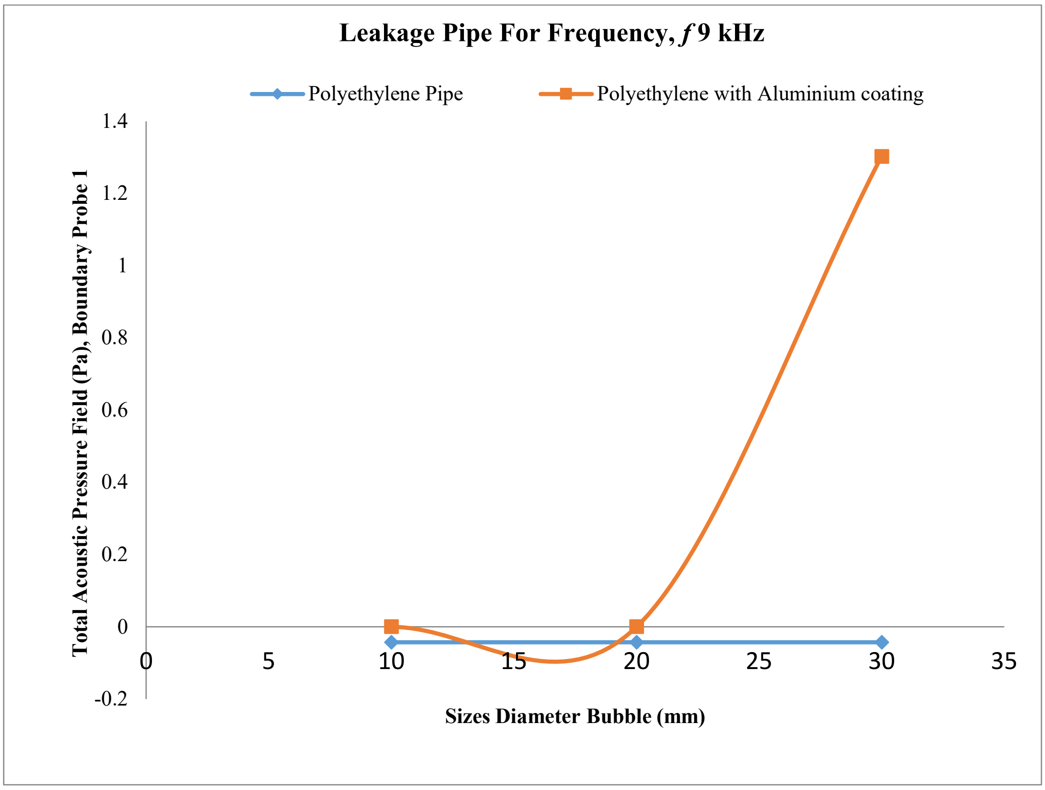

Figure 8: Graph acoustic pressure analysis with frequency, *f* 9 kHz

It can be summarized that the acoustic pressure in polyethylene pipe with aluminium coating shows the highest value of acoustic pressure for the biggest size of the bubble, 30mm. However, for 10mm and 20mm the pattern are non-linear. The size of the bubble, which serves as a disturbance, allows the acoustic pressure received by the piezoelectric receiver to be elevated during pipe leakage. However, for polyethylene pipe without aluminium coating, for 6Khz and 9Khz, it shows a steady line pattern where the acoustic pressure shows not much effect on the size of the bubble. It proves that the pipe with aluminium coating is more suitable to be used with piezoelectric sensor compared to the pipe without aluminium coating.

4. Conclusion

Leaks in water pipelines, sometimes caused by a variety of causes, such as the age of the pipe, improper construction, and natural disasters. A solution is necessary to identify and determine the position of the damage when there is a leak. From this work, it can be concluded that piezoelectric sensor is a useful solution in identifying the position of the damage relative to the real location of the leak with the appearing of water bubbles in the pipe. The signals transmitted by a piezoelectric transmitter will be blocked by the bubbles, and the strength of the receiving signal from the piezoelectric receiver will become weak. This could be an indicator of pipe leakage. The more suitable pipe to be used along with piezoelectric sensor is the polyethylene pipe with aluminium coating as it can become the good conductor for piezoelectric transducer. In the future, a piezo sensor-based leakage detection system can be carried out on branched pipelines along with various water flow rates usage.

Acknowledgement

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