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Acoustic Pressure Simulation for Fluid Piping Leakages

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ABSTRACT

Pipelines laid over long distances in the onshore environment may be affected by excessive straining, corrosion, the collapse of soil and other third-party damages. Small chronic leaks may cause severe safety and environmental effects if left undetected for a long time. Any potential onshore leaked water source may not be detected for a long time and could lose a considerable water source volume under the ground. Thus, this study aims to determine the leakage pipeline based on the acoustic analysis. Three different models of leakage pipeline had modelled: single leakage with 110mm in pipe diameter, single leakage with 185mm in pipe diameter and two leakages with 110m in pipe diameter. The computational fluid dynamic method was used to simulate the acoustic effect on the leakage pipeline. The results showed that the differential pressure to the leakage pipeline has a significant impact on the sound pressure level and turbulence kinetic energy. Furthermore, the turbulence kinetic energy was proportional to the sound pressure level through the comparison made for each model. Thus, this study manages to enrich the knowledge on the acoustic as well as facilitate understanding the behaviour of leakage pipes for future leaks detection analysis.

1. Introduction

Pipeline transport is the long-distance transportation of a liquid or gas through a system of pipes which is typical to a market area for consumption. Liquids and gases are transported in pipelines and any chemically stable substance can be sent through a pipeline. Pipelines exist for the transport of crude and refined petroleum, fuels such as oil, natural gas, and biofuels. As for shorter distance transport, pipelines were used for fluids including sewage, slurry, water, beer, hot water, or steam. It is also very important for transporting water for drinking or irrigation over long distances when it needs to move over hills, or where canals or channels are poor choices due to considerations of evaporation, pollution, or environmental impact. Today, global energy advancement for pipelines creates an increase of its application to 7% each year [1].

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Leaks are among the major threats to pipeline transport systems, which could be due to installation defects, corrosion, vessel grounding and mechanical impact. These would affect marines and human life in most cases associated with leaking pipelines failure [2]. In 2010, approximately 4.16 million liters of crude oil has contaminated the Talmadge Creek and Kalamazoo River in Michigan, North America due to pipelines leaking [3]. The occurrence of leaks in pipeline systems does not only signify a loss of valuable hydrocarbon resources but also a source of the environmental pollution and potential of disasters. The recent increase in the utilization of pipeline systems for oil and gas transportation together with the great economic loss and environmental implication associated with their failure calls for a need to explore cheap, quick, accurate and reliable leak detection methods in pipeline systems using real-time monitoring technologies.

The most common leaking problem is caused by corrosion. Corrosion is caused by an electrochemical process that the electron moves from the anode side to the cathode side by passing through an electrolyte [4]. By the time passing, the corrosion will be occurring at some location of pipeline structure. It occurs some unpredictable accident which is natural gas transmission pipeline ruptured. For example, natural gas transmission pipeline incident in Danville, Lincoln County, Kentucky. The ruptured pipeline released about 66 million cubic feet of natural gas which ignited, resulting in the death of 1 person, the hospitalization of 6 people and the evacuation of 75 residents from the Indian Camp mobile home park [5]. Hence, early detections of pipe leaks are very crucial.

Commonly, there are two types of leak detection and location systems which consist of externally based methods as well as internally based methods [6]. Exterior methods mainly involve the use of specific sensing devices to monitor the external part of the pipelines. These methods could be used to determine abnormalities in the pipeline surrounding and detect the occurrence of leakages. Irrespective of the working principles, these sensing methods are based on a physical contact between the sensor probes and the infrastructure under monitoring. Examples of these devices include acoustic sensing, fiber optic sensing, vapor sampling, infrared thermography, and ground penetration radar [7]. Interior or computational methods utilize internal fluid measurement instruments to monitor parameters associated with fluid flow in pipelines [8]. These systems are used to continuously monitor the status of petroleum products inside the pipeline such as pressure, flow rate, temperature, density, volume, and other parameters which quantitatively characterize the released products. By fusing the information conveyed from internal pipeline states, the discrepancy between two different sections of the pipeline can be used to determine the occurrence of leakage based on various methods, namely mass-volume balance, negative pressure waves, pressure point analysis, digital signal processing and dynamic modelling [6].

Previous studies have been investigating the fluid flow behavior at leak region affected by the changes in fluid velocity. Researchers such as Ong *et al.* [6] even use more than one leaking on a single pipeline. By using a computational fluid dynamic, CFD analysis, their 3D model of the subsea pipeline was simulated. This kind of simulation method use to investigate the leakage pipeline was also used by various research [9-13]. Hence, this study aims to study a leak's effect on the surrounding acoustic pressure by using CFD based simulation. A well-known ANSYS Fluent version 19.2 was used to carry out the simulation. This method could be used by pipeline operators to identify the sound wave of the environment and sound wave of an actual pipe leaking to differentiate other sound sources from actual pipe leaking based on leak detection technologies.

2. Methodology
2.1 3D Modelling

Three onshore pipeline model was drawn using Solidwork 2018 (Dassault Systèmes SolidWorks Corporation). All geometry of the pipeline involving length and leakage were in the same circular shape and was built with diameter of 8m and 4mm respectively. Figure 1 (a) shows first model (model 1) of pipeline with 0.110m diameter and a single number of leakages. Second model (model 2) in Figure 1 (b) was also having the same number of leakages as model 1 but with a different diameter of pipeline which was 0.185m. Third model or model 3 in Figure 1 (c) however was constructed with two (2) number of leakages located 4m away from each other which was pointed by the red arrow in the figure. A brief description of all three (3) model was mentioned in Table 1.

Table 1

Model	Pipe Diameter, (m)	Length of Pipe, (m)	Number of Leakage	Leakage Diameter, (mm)	Distance of Leakage from Pipe Inlet, (m)
1	0.110	8	1	4	4
2	0.185	8	1	4	4
3	0.110	8	2	4	2 (leak 1), 6 (leak 2)

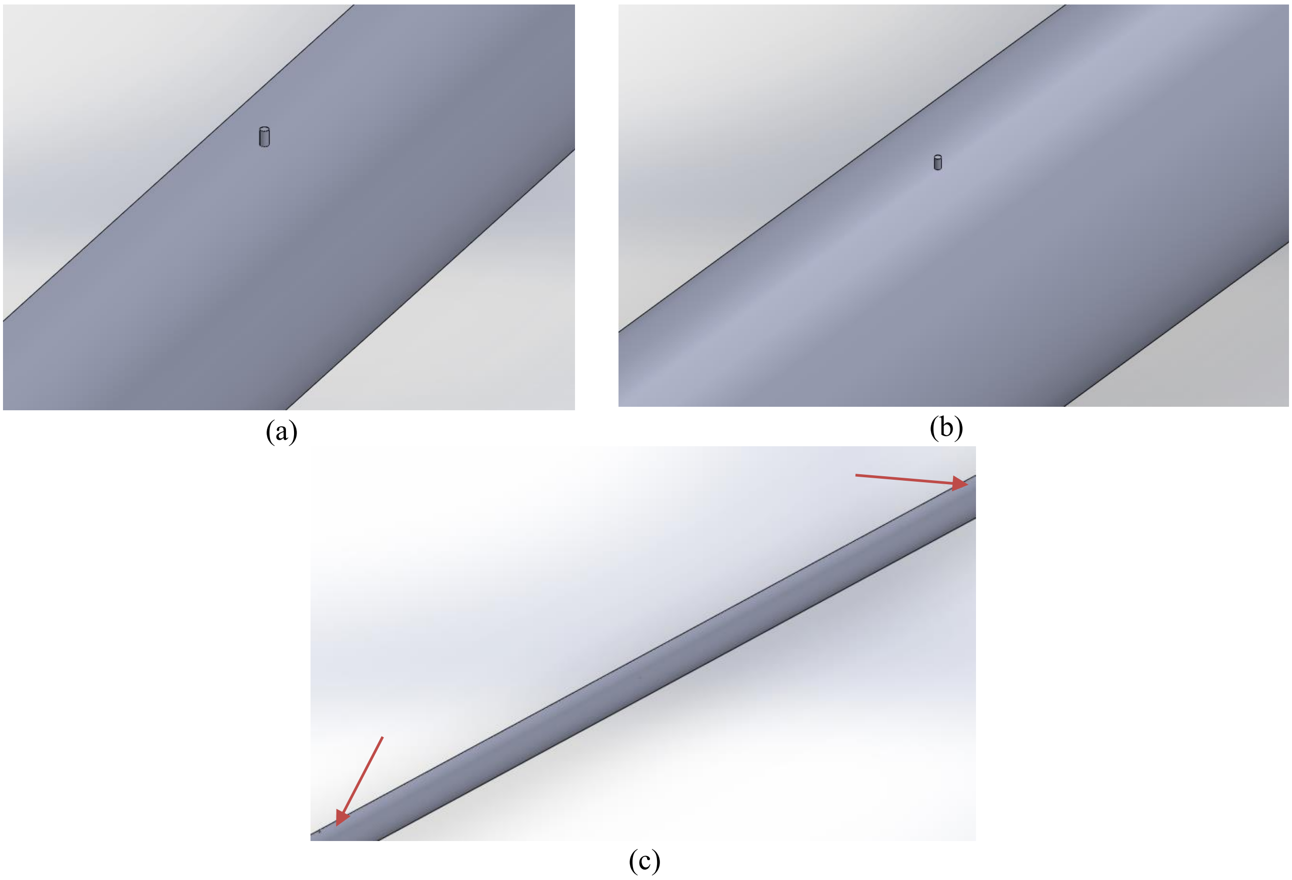

Fig. 1. (a) Model 1 with 8m long pipeline with one (1) 4mm diameter leakage, 110mm diameter, (b) Model 2 with 8m long pipeline with one (1) 4mm diameter leakage, 185mm diameter, and (c) Model 3 with 8m long pipeline with two (2) 4mm diameter leakage, 110mm diameter

2.2 Numerical Modelling

Simulation method is an efficient approach to investigate fluid flow behavior of interest and such approach has been used in many previous studies [6, 9]. For the present study, a Computational Fluid Dynamics (CFD) method analysis using ANSYS Fluent version 19.2 (ANSYS, Inc) to simulate the model was employed. ANSYS Fluent able to solve the continuity and momentum equations through mass conservation equation and the momentum conservations equations. In general, continuity or mass conservation equation was constructed as Eq. (1) below. This is valid for both compressible and incompressible flows. The mass contributed to the continuous phase from the dispersed second phase and any user-defined sources are referred to as the source, S_m.

$$\frac{\partial \rho}{\partial t} + (\nabla . \rho \upsilon) = S_{\mathrm{m}} \tag{1}$$

For momentum conservation equation the velocity field is shared throughout the phases after a single momentum equation is solved over the fluid domain [14]. Through the characteristic of ρ and μ, the momentum equation, illustrated in Eq. (2) below, is dependent on the volume fractions of all phases.

$$\frac{\partial}{\partial t}(\rho \vec{\upsilon}) + \nabla . (\rho \vec{\upsilon}\vec{\upsilon}) = -\nabla p + \nabla . (\vec{\tau}) + \rho \vec{g} + \vec{F} \tag{2}$$

The numerical model in this paper was simulated using the k- ε model based on Reynold's Average Navier-Stokes (RANS) equations, which is widely used in engineering turbulence steady state simulation for industrial applications [15]. Two equations, the kinetic energy, k, and the dissipation rate, related to turbulence, are solved in the turbulence k-ε model. The k-ε model is based on the Eddy viscosity principle, in which the turbulence-causing effective eddy viscosity is described as

$$\mu_{eff} = \mu + \mu_t \tag{3}$$

μt is the turbulent viscosity in Eq. (3), which is related to turbulent kinetic energy and dissipation rate. The fluid density, ρ is constant, as is the turbulence coefficient, $C\mu$. The turbulent viscosity, commonly known as the Eddy viscosity, is computed in Eq. (4) as follows:

$$\mu_t = \frac{\rho C_\mu k^2}{\varepsilon} \tag{4}$$

Because of the high Reynolds number, $C\mu$ is a model constant, and its default value of 0.09 was employed in this investigation. Solving their conservation equations yields the turbulence kinetic energy, k, and turbulent dissipation rate, ε. The conventional k-ε-turbulence model's conservation equations are listed in Eq. (5) below. The kinetic energy of turbulence can be expressed as:

$$\frac{\delta(\rho k)}{\delta t} + \frac{\delta(\rho k u_i)}{\delta x_i} = \frac{\delta}{\delta x_j}\left(\frac{\mu_{eff}}{\sigma_k}\frac{\delta k}{\delta x_j}\right) + G_k - \rho_\varepsilon \tag{5}$$

2.3 Boundary Condition

After that, the geometry of three models were imported into ANSYS Workbench 19.2 for steady-state simulation. A sets of boundary conditions were applied to replicate an actual subsea pipeline flow situation. The velocity water of 1.524m/s was employed at the inlet of the pipeline indicating inlet velocity. A gauge pressure ranging from 1 to 5 bar was set at the out boundary to make the simulation as significant as the actual scenario. A zero-gauge pressure was used at the leakage to replicate the water flows is exposed to the atmospheric conditions. A non-slip wall boundary conditions was used on the pipeline wall.

2.4 Verification of Model

Verification of simulation is done based on Ong Yong Wei *et al.,* [6] with a relative percentage error within 5% of error. A subsea pipeline model with 0.322 m diameter, 8 m in length, and a circular 5 mm diameter of leaking which located at 4 m from the inlet of the fluid domain was used [6, 10]. The subsea pipeline velocity level used in this process was following previous study by Ong *et al.*, Masour *et al.*, and Jujuly *et al.* [6, 10, 16]. Previous study shows that the pressure distribution along pipelines for different velocity of P_{line} = *5300 psi* at surface centerline were 3.6547 e^7 Pa while current simulation produced 3.6549 e^7 Pa. According to the verification process, the pressure distribution for the leaking of pipeline model creates a sudden drop in all velocity value studied as shown in Figure 2. After a verification of model is done, the grid independency test was carried out before acoustic analysis according to objectives could be done.

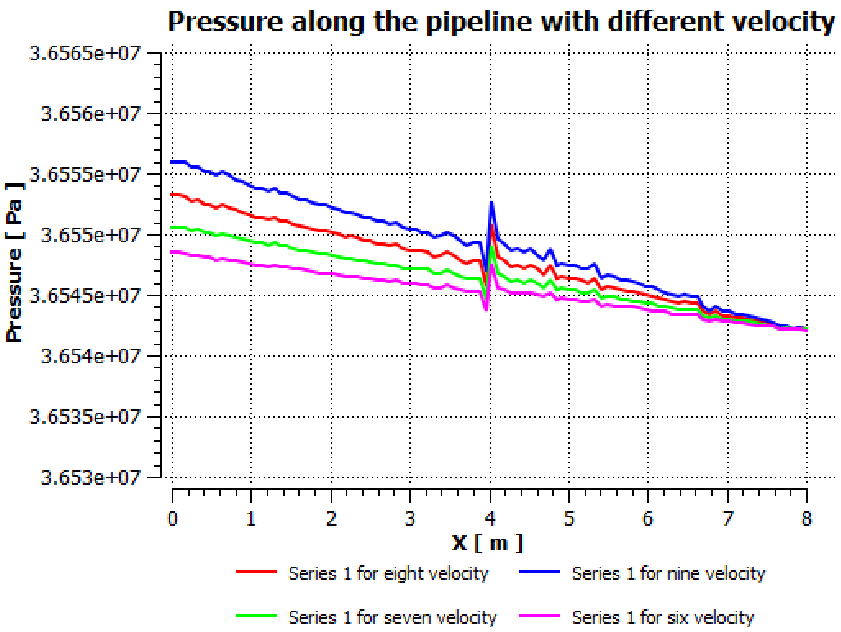

Fig. 2. Pressure distribution along pipeline for different fluid velocity of 6 to 9 ms^{-1}

3. Results

3.1 Grid Independent Test

Grid independency test, GIT is a method to use in constructing a discretization process for the simulation model. This is to ensure the results are accurate based on its meshing construction with appropriates meshing setup. The results must be independent enough from the changing of the mesh discretization so it could be taken as a significant data. Considering the results in Table 2 and assuming the GIT with less than 1% in the predicted sound pressure level, therefore the solution obtained using mesh two are mesh independent and hence this mesh is used for the rest of the computation for model 1. The following tables (Table 3 and Table 4) shows the GIT results for model 2 and model 3 respectively. Based on Table 3, the third mesh setup was used for model 2 while third mesh setup in Table 4 was used for model 3.

Table 2
GIT table of Model 1

Mesh	Number of nodes	Number of elements	Skewness	Sound pressure level
1	112467	554406	0.80305	51.2297
2	207714	1039186	0.82140	50.9484
3	307772	1561206	0.82435	51.0458
4	411611	2105984	0.82978	51.0395

Table 3
GIT table of Model 2

Mesh	Number of nodes	Number of elements	Skewness	Sound pressure level
1	104832	522777	0.8213	49.913
2	207354	1058636	0.81038	49.6669
3	301185	1537963	0.81868	49.7688
4	408604	2104013	0.8212	49.8658

Table 4
GIT table of Model 3

Mesh	Number of nodes	Number of elements	Skewness	Sound pressure level
1	107033	526191	0.79614	51.4437
2	207739	1039074	0.79935	51.2464
3	298139	1511133	0.82148	51.0662
4	397059	2028439	0.82459	50.9472

4. Result and Discussion

4.1 Sound Pressure Level (SPL) of Model 1 Pipe Leaking

Figure 3 shows the distributions of SPL for the first model with various pressure differences at the water pipeline. The initial stage of SPL within the pressure's differences were almost similar. The data shows that the SPL value ranging between 50dB to 52dB as it flows inside the pipeline model. As the water flows approaching the leakage, the SPL value increases significantly for every pressure level. This started to happen at 2.5m from pipeline inlet or 1.5m before the leakage. The SPL keep on increasing until it reaches the leakage at 4m from the inlet. At this stage, all five level of pressure produced high SPL level in which pressure of 5bar shows the highest SPL of 60.5dB.

Figure 4 shows the kinetic turbulence energy of 5 differences pressures. The relationship of turbulence kinetic energy between pressures was similar as shown in the SPL. As the water flows from inlet of the pipeline, the turbulence kinetic energy creates a continuous behavior ranging from $0.014m^2s^{-2}$ to $0.016m^2s^{-2}$. A rapid change of turbulence kinetic energy occurred at the leakage of the pipeline which located at 4m from inlet. This sudden change was produced by all pressure level. The turbulence kinetic energy with 5bar pressure creates the highest value which is $0.0417m^2s^{-2}$ while the lowest was recorded by 1bar pressure with $0.026m^2s^{-2}$. After passing the leakage area, the reading drop back to previous behavior.

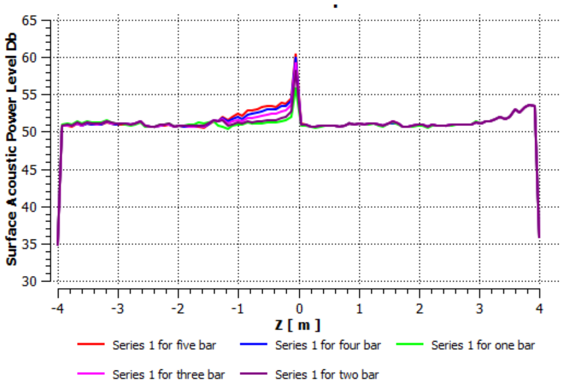

Fig. 3. SPL along the model 1 pipeline with 5 different bar

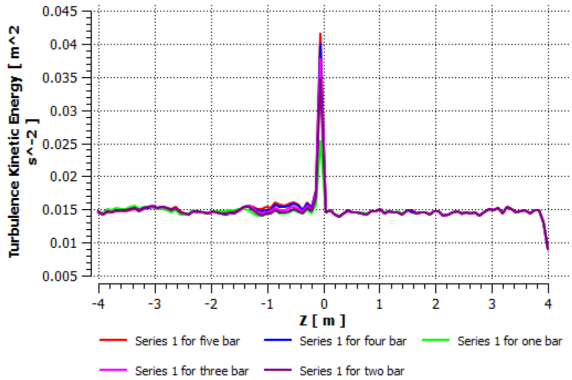

Fig. 4. Turbulence Kinetic Energy along the model 1 pipeline with 5 different bar

4.2 Sound Pressure Level (SPL) of Model 2 of Pipe Leaking

Figure 5 shows the distributions of SPL for model 2 with various pressure differences at the water pipeline. These results were similar behaviour of SPL as shown in Figure 3. However, the SPL values for Model 2 were quite fluctuated at the beginning of the pipeline and no more high activity of SPL was seen before reached the leakage area as shown in Model 1. The highest SPL value was seen for pressure with 5 bar which is approximately 58.4dB. The discrepancy was calculated between models 1 and 2 approximately 3.5 per cent. After moving through the leak area, SPL drop back to previous sound level. Before reaching to the endpoint of the pipeline, the sound pressure level started to increase again and then drop back to its initial sound level when reach the endpoint of pipeline.

Figure 6 shows the turbulence kinetic energy along with model 2 for various pressure differences. From the observation, the distribution of turbulence kinetic energy was similar and sharply increase at the leakage area. The loss of turbulence kinetic energy and the pressure drop might be disturbed the water supply as well as waste the resources. The detection of the leakages through the analysis of turbulence kinetic energy might be used as a method to calculate the waste of water supply. From the figure, the pressure with 5 bar was seen as the highest value of turbulence kinetic energy approximately $0.0375m^2s^{-2}$ which representing the highest waste of water resources due to the leakages.

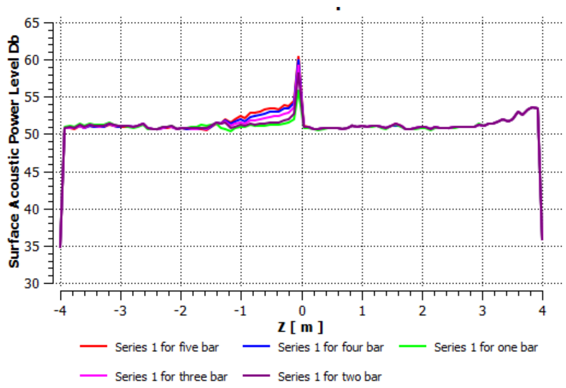

Fig. 5 SPL along the model 2 pipeline with 5 different bar

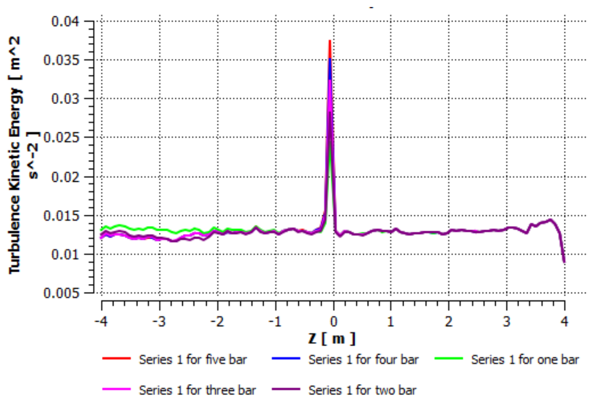

Fig. 6 Turbulence Kinetic Energy along the model 2 pipeline with 5 different bar

4.3 Sound Pressure Level (SPL) of Model 3 of Leakage Pipeline

The distributions of the SPL of model 3 for 5 different pressure is illustrated in Figure 7. This model has two different location of pipe leakage as also explained in Figure 1(c). From the observation, the distribution of SPL for this model quite different as compared to models 1 and 2. Two peaks value were seen along the pipeline representing the leakages area. However, the first peak values were slightly lower than the second leakage approximately 57.38 dB and 67.8 dB respectively. The distribution of the SPL at the leakage area was seen in line with the direction of flow which that the SPL value reduced abruptly away from the area of the leakage in the direction of flow as seen in Figure 7.

The distributions of turbulence kinetic energy were also seen the double peak as shown in Figure 8. From the result, the pressure with the 5 bar shows the highest value of turbulence kinetic energy for both double peak which contributed about 0.0298 m^2s^{-2} and 0.0867 m^2s^{-2} respectively.

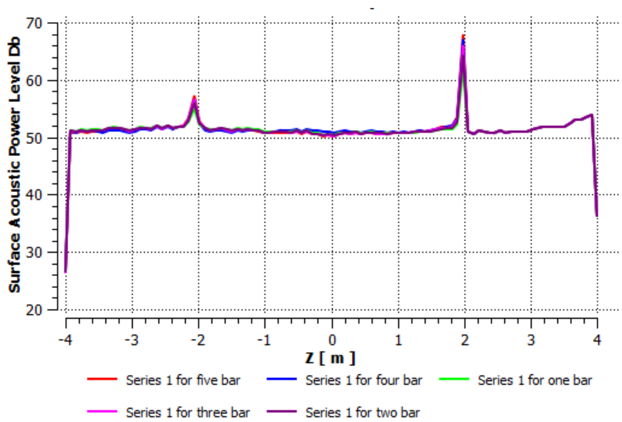

Fig. 7. SPL along the model 3 pipeline with 5 different bar

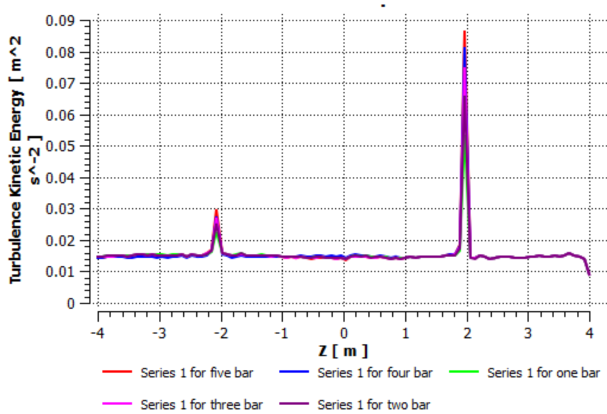

Fig. 8. Turbulence Kinetic Energy along the model 3 pipeline with 5 different bar

From the observation, the SPL value was seen slightly lower when the diameter of the pipe was increased as shown in Figure 3, 5 and 7. The increase of the diameter of the pipe has influenced the deduction of turbulence kinetic energy as well reduced the SPL values. The deduction of the turbulence kinetic energy was due to the presenting of the swirling eddies at the area of the leakage for all models. However, model 3 presenting the worst condition in terms of SPL value as well as turbulence kinetic energy due to the appearances of two different locations of leakages.

5. Conclusions

From the results, the SPL value is higher for all difference pressures at model 2 as compared to model 1 for the area of the single leakage. However, the SPL value for double leakages model (model 3) become worst as compared to model 1 and 2. This phenomenon caused the deduction of SPL value twice in the pipeline which influence the turbulence kinetic energy. The turbulence kinetic energy was also influenced by the different pipe diameters which the higher the diameter, the lower of SPL was recorded.

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