CFD Letters 11, Issue 2 (2019) 95-107

CFD Letters

Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

Computational Fluid Dynamics Analysis on Single Leak and Double Leaks Subsea Pipeline Leakage

Open Access

Ong Yong Wei[1], Siti Ujila Masuri[1,*]

[1] Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 21 September 2018
Received in revised form 6 January 2019
Accepted 2 February 2019
Available online 14 February 2019

Keywords:
Computational fluid dynamics, subsea pipeline, pipeline leakage

ABSTRACT

This paper describes the numerical investigation on single leak and double leaks subsea pipeline leakage using ANSYS FLUENT based on standard k-ε model under steady-state condition. The simulation is done to investigate the effect of fluid velocity and emergence of second leak on the leak flow rate, pressure distribution and turbulence kinetic energy at near leak region and compare those flow parameters between single leak and double leaks subsea pipeline models. The simulations results show that the change of pipeline fluid velocity only has little impact on the flow behavior at leak region. The emergence of second leak does not cause much effect on the flow behavior at first leak. When both models are compared, the leak flow rate at first leak is always higher than that of the second leak. Pressure distribution disturbance due to leak is much more significant at second leak as compared to first leak while vice versa for turbulence kinetic energy along the subsea pipeline.

1. Introduction

Pipeline leakage is a common phenomenon occurs on any transporting pipelines which may results from sudden change of pressure, corrosive action, cracks, defect in pipes, bad workmanship, any destructive causes as well as lack of maintenance [1]. The consequences of pipeline leakage are enormous if it is not handled immediately or carefully. Other than water transporting pipelines, subsea pipelines are also used to transport hydrocarbons and natural gas. A failure in oil transporting pipeline due to leak will cause oil spills into the sea region and leaves negative impact to human health as well as marine lives [2]. For example, 1.1 million gallons of crude oil has been released to Talmadge Creek and Kalamazoo River at Michigan (north of United States of America) in year of 2010 [3]. In 2014, Enbridge Inc. who is responsible for the oil spillage has spent $1.21 billion USD for cleaning up the contaminated regions and another $177 million USD to settle civil penalties and future operational costs [4]. Pipeline leakage not only causes property and revenue loss but also loss of energy, and risking human lives as well as marine animals. Thus, various leak detection and location methods have been developed based on flow parameters like flow rate, pressure change and acoustic

[*] *Corresponding author.*
E-mail address: ujila@upm.edu.my (Siti Ujila Masuri)

signal and more researches are still undergoing in order to have better insight on the flow behavior of leaked fluids at inner and outer parts of transporting pipelines.

Generally, there are three categories of leak detection and location systems which include visual inspection, internally based methods as well as externally based methods. One of the visual inspection method is by using Ground Penetration Radar (GPR) to obtain the radargram to inspect water leakage underground as proposed in Halimshah *et al.,* [5]. Externally based method uses fiber optic or dielectric cables integrated along pipelines to detect leaks. As for internally based methods, flow behavior of fluids inside pipeline such as pressure, temperature or flow rate are monitored and analyzed through computation [6]. Internally based methods can also be defined as model-based method, negative pressure wave (NPW)-based method, acoustic based method and transient-based method [6]. Most common methods used in detecting pipeline leakage are based on the flow parameters as it is reliable and considerably accurate. These include negative pressure wave (NPW), integrated signal (SI) and acoustic signal methods.

Negative pressure wave (NPW) method detect leaks by sensing the pressure change using sensor installed at both ends of a pipeline which later on modelled by mathematical modelling [6]. However, it is difficult to detect pressure change caused by small or slow leakage of long pipelines. Thus, the integrated signal method is proposed in Sun *et al.,* study [6] which uses signals generated simultaneously from pressure and flow rates. The integrated signal is generated from the transient simulation of the leakage and able to detect small and slow leaks due to the more significant increase in leakage-induced signal change.

Acoustic method monitors the dynamic pressure obtained from acoustic sensor which can display full scale pressure fluctuations caused by leakages [7]. Acoustic signal is generated by the interaction of fluids and pipe wall in the form of elastic wave travelling upstream and downstream which then captured by acoustic sensor. A leak detection method based on time-frequency analysis of leak acoustic wave is proposed by Kim *et al.,* [8] to detect leaks in gas pipelines. Based on the results obtained, time-frequency analysis method is a better analysis than power spectrum density (PSD) in identifying the cut-off frequencies of the acoustic signal. Since a real pipeline always present with background noise, so by using the time-frequency analysis, bandwidth of filter can be easily selected to obtain information on the leakage position [8].

Moreover, most of the leak location method recently is based on the velocity and time-difference of two measured signals calculated by cross-correlation method [9]. However, Cui-wei *et al.,* [7] states that acoustic leak detection and location system is always restricted by the accuracy of the velocity and time-difference of signals. Thus, a location method based on propagation model independent from velocity and time difference is proposed by Lui *et al.,* [10]. Jin *et al.,* [11] Proposed a combination of leak detection and location method model for gas pipelines. A modified acoustic velocity and location formula is proposed in which the spread velocity of acoustic waves in pipeline is based on properties like density, pressure and specific heat of the medium.

Previous studies have been carried out to investigate the fluid flow behavior at leak region due to normal condition, subsea condition, sizes of leak as well as the change of pressure. The impact of leak sizes and change in pressure on the flow behavior of single leak subsea pipeline has been carried out in Jujuly *et al.,* study [12] but double leaks subsea pipeline has yet to be discussed. Besides that, a pipeline leakage model with two leaks is also proposed by De *et al.,* [13] but simulated under transient condition to monitor the effect of emergence of another leak at certain time when there is already a leak existed on the same pipeline. However, studies based on effect of high fluid velocity on single leak and double leaks pipeline leakage under subsea conditions are yet to be discussed. Two independents studies have been performed on single leak and double leaks water pipeline to study the effect of number of leaks and pressure change on fluid flow behavior due to leakage in [1] and [14] but no direct comparison has been done. Thus, this paper focuses on the effect of change in fluid velocity and emergence of second leak present simultaneously with the first leak on the subsea pipeline fluid flow behavior at leak region. Furthermore, comparison between single leak and double leaks subsea pipeline leakage models is discussed in the present study.

2. Methodology

Simulation method is an efficient approach to investigate fluid flow behavior of interest and such approach has been used in many previous studies [1-2, 12-15]. For the present study, a Computational Fluid Dynamics (CFD) analysis was employed whereby a subsea pipeline model of 0.322 m diameter with a length of 8 m was constructed using Solidworks with first leak located at 4 m and second leak at 6 m away from the inlet section. Both leaks were assumed to be circular and have 5 mm diameter following the model proposed in Jujuly *et al.,* [12]. Figure 1 shows 2-D illustration of single leak model while Figure 2 shows that of double leaks model. The geometries of both models were then imported to ANSYS Workbench 14.5 for simulation purposes under steady-state condition. The simulation was done using standard k-ε model which is relatively sufficient to capture the turbulence feature of the flow.

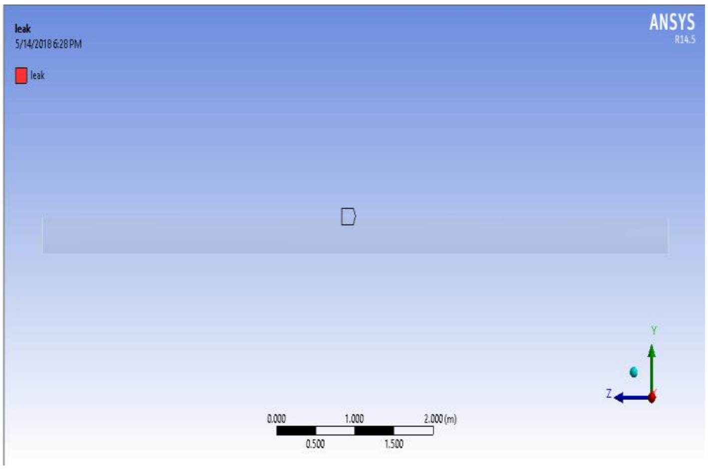

Fig. 1. 2-D illustration of single leak subsea pipeline model

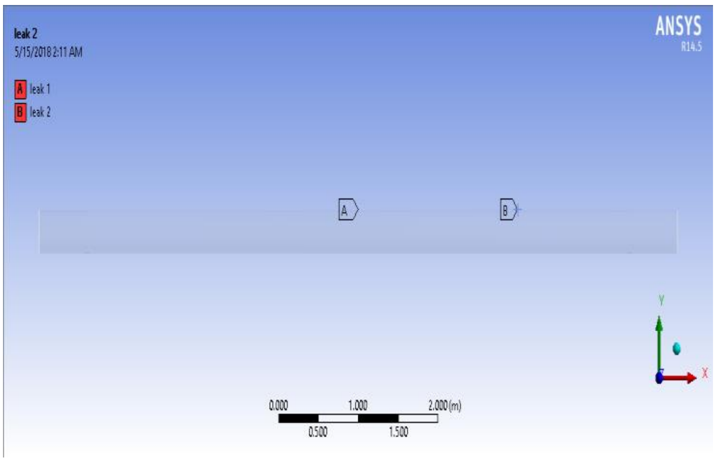

Fig. 2. 2-D illustration of double leaks subsea pipeline model

2.1. Numerical modeling

The numerical model in this study was simulated with Reynold's Average Navier-Stokes (RANS) equations based k-ε model which is commonly used in performing engineering turbulence steady-state simulation for industrial applications [12]. In the turbulence k-ε model, two equations, the kinetic energy, k and dissipation rate, ε due to turbulence are solved. The k-ε model based on the eddy viscosity concept where the effective eddy viscosity responsible for the turbulence is modelled as [12]:

$$\mu_{eff} = \mu + \mu_t \tag{1}$$

In Eq. (1), μ_t is the turbulent viscosity which linked to turbulent kinetic energy and dissipation rate. The fluid density, ρ and turbulent coefficient C_μ are constant. The turbulent also known as the eddy viscosity is calculated by combining k and ε as follow [16]:

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

C_μ is a model constant and its default value is 0.09 will be used in this study due to high Reynolds number. The turbulence kinetic energy, k and turbulent dissipation rate, ε are obtained by solving their conservation equations. The conservation equations of standard k-ε turbulence model is given below. The turbulent kinetic energy can be described as [16]:

$$\frac{\delta(\rho k)}{\delta t} + \frac{\delta(\rho k u_i)}{\delta x_i} = \frac{\delta}{\delta x_j}\left(\frac{\mu_{eff}}{\sigma_k}\frac{\delta k}{\delta x_j}\right) + G_k - \rho_\varepsilon \tag{3}$$

The turbulent dissipation rate can be described as [16]:

$$\frac{\delta(\rho \varepsilon)}{\delta t} + \frac{\delta(\rho \varepsilon u_i)}{\delta x_i} = \frac{\delta}{\delta x_j}\left(\frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\delta \varepsilon}{\delta x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{4}$$

G_k and G_b represent the generation of turbulent kinetic energy due to mean velocity gradient and buoyancy respectively. The model constant for $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k, σ_ε have the following default values according to ANSYS FLEUNT standard k-ε turbulence model [16]:

$$C_{1\varepsilon} = 1.44,\ C_{2\varepsilon} = 1.92,\ \sigma_k = 1.0,\ \sigma_\varepsilon = 1.3.$$

2.2. Mesh Independence Study

Three sets of meshes with same simulation conditions were performed under the same boundary conditions for subsea pipeline leakage model [12]. The boundary conditions for the flow model include velocity inlet of 9 m/s, leak pressure outlet similar to pressure 100 m under sea level which is 150 psi and pressure outlet at the exit of pipeline of 5300 psi. The properties of the mesh along with its respective leak flow rates are presented in Table 1.

Table 1
Mesh independence study (P_{line} = 5300 psi and v = 9 m/s)

Mesh	Number of elements	Leak flow rates (L/s)
M1	554717	4.7878
M2	1190903	4.9525
M3	1669433	4.9669

Based on the results obtained, mesh 2 was picked for performing the rest of the simulations as it not only gave considerable accurate results but also a lower computational cost comparing with mesh 3.

2.3. Boundary Conditions

In order to simulate a real subsea pipeline flow situation, the following boundary conditions were used:

Inlet Boundary Conditions: Velocity-inlet is used with water velocity ranging from 6 to 9 m/s to avoid the effect of erosion.

Outlet Boundary Conditions: Pressure-outlet is used with pipeline pressure according to normal subsea pipeline standard of 5300 psi and 5800 psi for simulation in present study and result validation with [12] respectively.

Leak Boundary Conditions: Pressure-outlet is used and pressure is assumed to be 150 psi which is similar to that of pressure at 100 m below sea surface following [12].

Wall Boundary Conditions: A default wall roughness value and non-slip condition are used in the present study.

3. Results

3.1. Single Leak Subsea Pipeline Model

Table 2 represents the effect of pipeline fluid velocity on the leak flow rate. As can be seen in Table 2, each 1 m/s increment of fluid velocity causes an increment of roughly 0.003 L/s which is also equivalent to 0.18 L/min of fluid escaping from the leak. However, the impact of change of fluid velocity on leak flow rate is incomparable to studies done in [1] and [12]. The pressure distribution of flow at leak region for different fluid velocity is presented in Figure 3. It is observed that the pressure distribution experience a sudden drop before increasing to its maximum at leak vicinity regardless of the pipeline fluid velocity. However, the change in pipeline fluid velocity has only little impact on the sudden pressure change at leak vicinity.

Table 2

Leak flow rate for different fluid velocity at P_{line} = 5300 psi

Fluid velocity (m/s)	Leak flow rate (L/s)
6.0	4.9481
7.0	4.9517
8.0	4.9550
9.0	4.9580

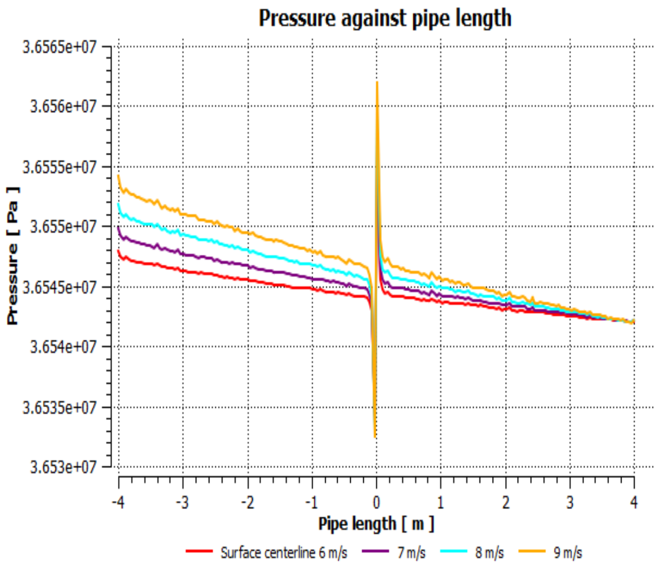

Fig. 3. Pressure distribution along pipeline for different velocity of P_{line} = 5300 psi at surface centreline

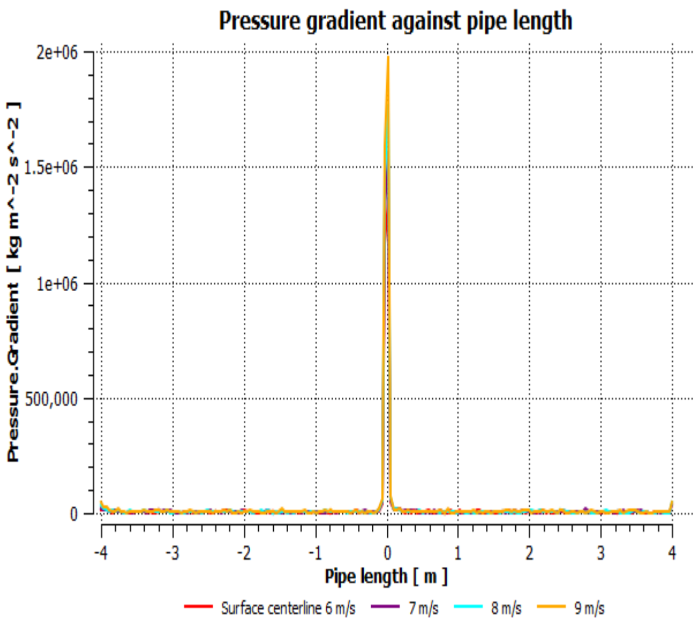

Fig. 4. Pressure gradient along surface centerline for different fluid velocity at P_{line} = 5300 psi

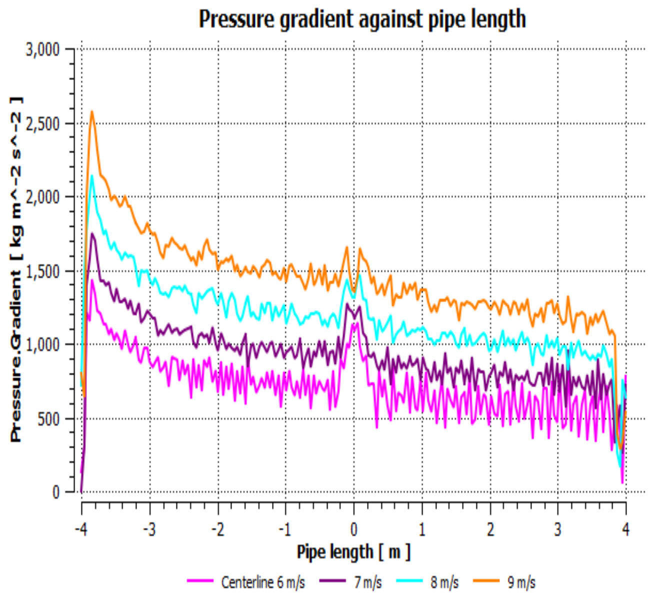

Fig. 5. Pressure gradient along centerline (y = 0) for different fluid velocity at P_{line} = 5300 psi

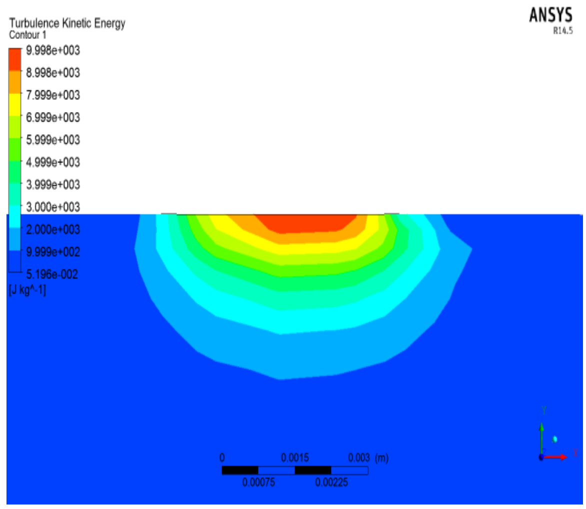

Fig. 6. Turbulence kinetic energy contour at leak region

The sudden change of pressure distribution of fluid flow along pipeline at leak vicinity causes a very significant spike of pressure gradient signal which makes the leak easily to be detected. This can be understood by looking at Figure 4. However, when the measurement moves away from the leak surface centerline to the center of pipeline, the pressure gradient signal has weakened and it's almost negligible as can be seen from Figure 5. This makes the leaks hardly detectable if sensors were to place at center of pipeline. As for the turbulence kinetic energy of fluid flow at leak region, the fluid experiences a sudden increase of turbulence kinetic energy due to the leak. It increases from 0.05196 J/kg which is the turbulence kinetic energy of flow of the pipeline to 9.998 kJ/kg at leak vicinity and decreases back to its initial value. Thus, the turbulence kinetic energy can also be served as an assisting parameters in leak detection in avoiding false signal alarm (Figure 6).

3.2. Double Leaks Subsea Pipeline Model

Table 3 represents the impact of change in fluid velocity on the leak flow rate. It can be seen from the table that flow rate at both leaks increase with the increase of pipeline fluid velocity. Flow rate at leak 1 is always higher than that of leak 2. However, the effect of change of fluid velocity only has minimal impact on the change of leak flow rates.

Table 3
Leak flow rate for different fluid velocity at P_{line} = 5300 psi

Fluid velocity (m/s)	Leak 1 flow rate (L/s)	Leak 2 flow rate (L/s)
6.0	4.9577	4.9493
7.0	4.9615	4.9521
8.0	4.9649	4.9548
9.0	4.9681	4.9571

The pressure distribution along the pipeline still experience a disturbance when second leak emerged at 2 m away from the first leak as can be observed from Figure 7. The pressure change is almost similar at both leaks with different pipeline pressure at respective leaks. The disturbance of signal is more significant in pressure gradient generated from the simulation result as can be seen in Figure 8. At 25 mm below the leak surface centerline, the pressure gradient signal is larger than that in second leak as compared to first leak. As the measurement moves away from the leak surface, the signal is hardly noticeable.

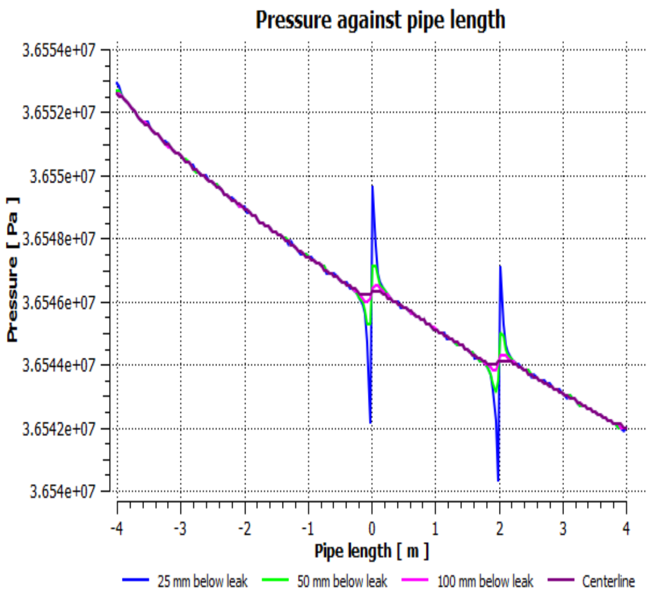

Fig. 7. Pressure distribution along pipeline for different positions at P_{line} = 5300 psi and v = 9 m/s

The pressure gradient contour serves the same purpose as graph in noticing the sudden change of pressure gradient at leak region as shown in Figure 9. The extreme change of pressure gradient is in the range of -1.411 x 1010 Pa/m and 1.481 x 1010 Pa/m at entrance edge of leak and exist edge of leak respectively. The extreme value of change in pressure gradient signal can be used by leak detection system to enhance the detection performance.

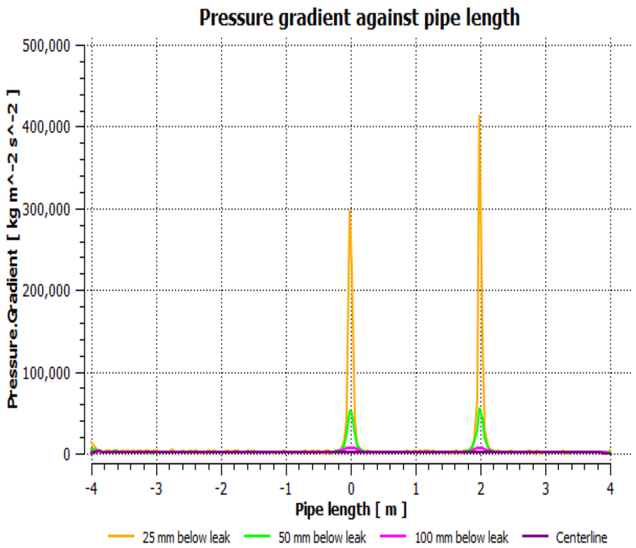

Fig. 8. Pressure gradient along pipeline for different positions at P_{line} = 5300 psi and v = 9 m/s

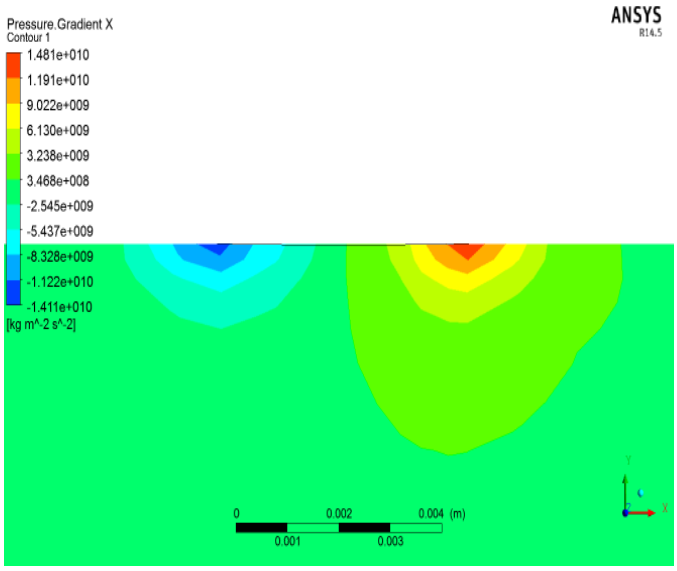

Fig. 9. Pressure gradient contour along pipeline at leak region

Also, the fluid flow experience a sudden increase of kinetic energy due to turbulence at leak vicinity. However, the increase of kinetic energy due to turbulence for fluid flow at leak 1 is higher than that in leak 2 which is believed to be responsible for the higher leak flow rate at leak 1 as compared to that at leak 2. Furthermore, the same observation can be noticed in Figure 10 is that the change in kinetic energy of fluid flow due to turbulence is almost constant as the measurement moves further away towards the center of the pipeline.

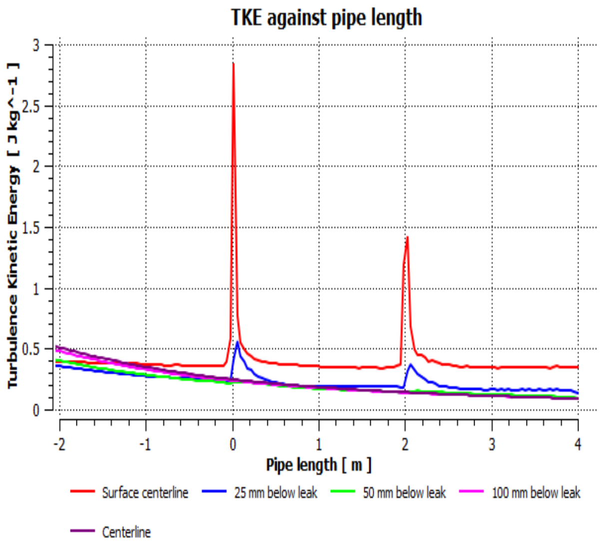

Fig. 10. Turbulence kinetic energy along pipeline at different position with P_{line} = 5300 psi and v = 9 m/s

3.3. Comparison of Flow Parameters between Single Leak and Double Leaks Subsea Pipeline Models

In order to compare the flow parameters at leak region between single leak and double leaks subsea pipeline models, both models with conditions of 5300 psi pipeline pressure and 9 m/s fluid velocity are chosen. For flow rates at leaks region presented in Table 2 and Table 3, leak flow rate for single leak model where leak located at the middle section of pipeline is 4.9580 L/s while 4.9681 L/s for the leak flow rate of leak at same position for double leaks model. The emergence of a new leak can be assumed that only affect slightly on the leak flow rate at the first leak but this slight increment of 0.606 L/min of flow rate is enough to cause enough of loss in energy in water transportation and major oil spill in sea environment. Thus, the integrated signal method based on pressure and flow rate signals proposed in [6] can be employed in this case for early detection to prevent more loss of wastage.

For the pressure behavior, pressure variation and pressure gradient signatures at the surface centerline and region 50 mm below the leaks surface along the pipeline are observed and compared. It is noticed that there is almost no difference for the pressure variation along the pipeline except at leak regions as shown in Figure 11 and Figure 12. The pressure change at leak 1 (x = 0) for both models are same which fluctuating between 36.523 MPa and 36.560 Mpa. At the regions 50 mm below leak, the trend of the graph for both subsea pipeline leakage models are the same except for a slightly higher pipeline pressure in single leak model. However, both models reaches the same pipeline pressure value after passing through the second leak. These show that there is little to no impact on the pressure distribution at leak 1 when there is emergence of leak at position 2 m away from leak 1.

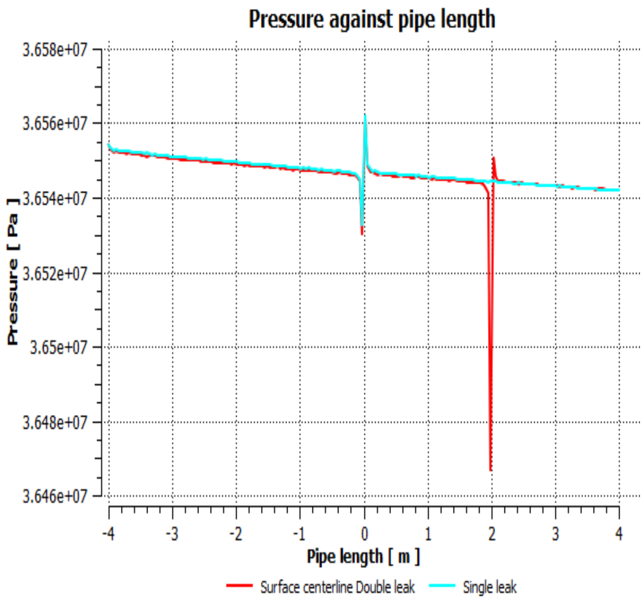

Fig. 11. Pressure distribution at surface centerline for single leak and double leak subsea pipeline models

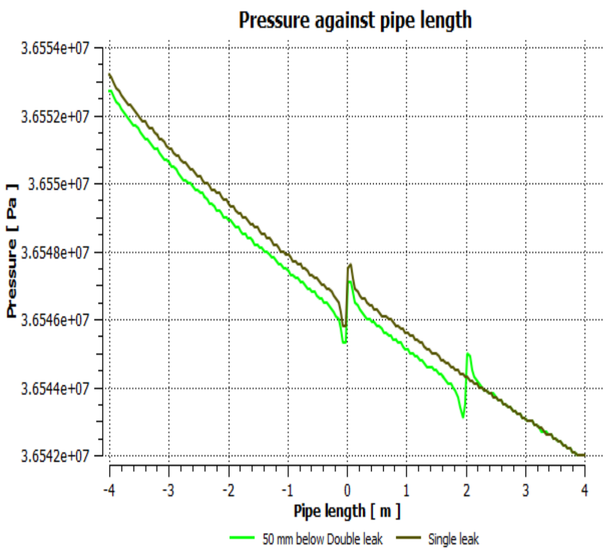

Fig. 12. Pressure distribution at 50 mm below leak for single leak and double leaks subsea pipeline models

As for the pressure gradient observed along pipeline at pipe surface centerline and 50 mm below leak in Figure 13 and 14, the same observation is noticed as there is little to no difference at all for pressure gradient measured at the first leak. Thus, it can be further proven that the emergence of another leak does not affect the pressure behavior at first leak region although at second leak the pressure and pressure gradient signature is always more significant. When a leak detection system based on pressure signal notice a large fluctuation in pressure or pressure gradient, it is assumed that there is leakage occur at the pipeline but should observe in detailed as there is maybe another leak occurs nearby based on the results obtained here.

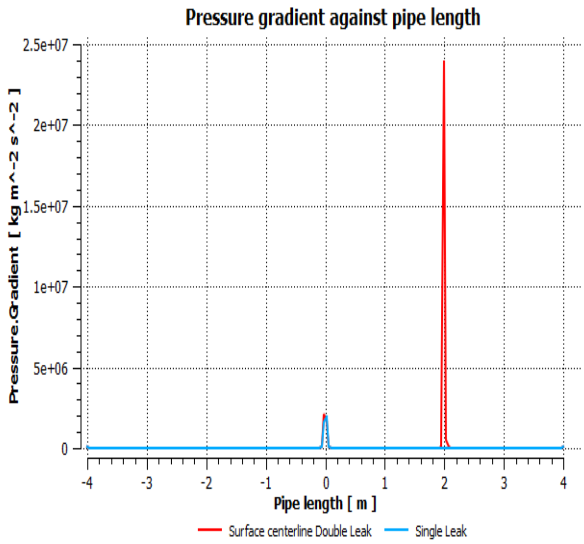

Fig. 13. Pressure gradient at surface centerline for single leak and double leaks subsea pipeline models

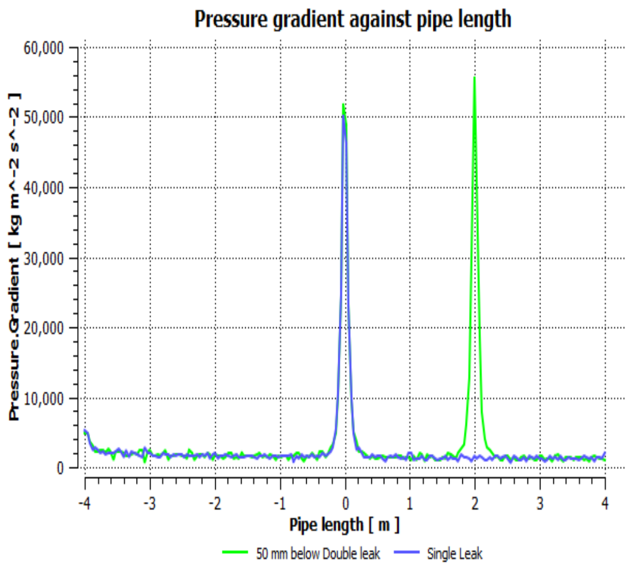

Fig. 14. Pressure gradient at 50 mm below leak for single leaks and double leaks subsea pipeline models

4. Conclusions

From this study it can be concluded that when the fluid velocity increases, the flow rates at both leaks increase but flow rate of leak 1 is always higher than that of leak 2. The pressure variation, pressure gradient and kinetic energy of flow due to turbulence always experience a fluctuation at leak regions which makes leak detection easier due to strong signals experienced at surface centerline. However, the signals of these parameters weaken as the measurement moves away from the leak region towards the pipe centerline. Thus, the objectives of the present study are achieved and leak detection system is best to be installed at the surface centerline of the pipeline. Future study on multiphase flow is recommended since this study only focus on single phase flow modelling under steady-state condition.

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