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Development of Model and Graphical User Interface for Leak Localization in Crude Oil Pipeline

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Pipelines provide the most efficient and cost-effective means for fluid transport but the challenge posed by leaks has substantially increased the risks and hazards in pipeline fluid transportation. The development of efficient leak detection system pays off in quicker leak detection and localization, leading to quicker responses and remediation works by the pipeline emergency response team. This would ultimately bring about less severity of the pipeline leak in terms of financial losses, human and environmental consequences. Steady state modeling of crude oil

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pipeline flow with attempt to determine and localize leak has been achieved in this study. Mathematical models have been developed to detect and localize leaks in crude oil pipeline during leak occurrence. Leak detection was modeled using the conservation of mass equation while leak localization was modeled by modifying the Darcy-Weisbach pipeline liquid flow equations and utilizing the Swamee-Jain friction factor correlation. Equations for flowrate and pressure drop along the pipeline were developed for two cases: a case where there is no leak in the pipeline and a case where there is leak in the pipeline. Leak localization equation was determined by equating the fluid flow equation when there is no leak and when there is leak. The model was structured and simulated in Matlab software with the model tested for four field cases. The results from the simulation revealed swift leak detection, accurate localization of the leak, and determination of the pressure at the point of leak. Experimentally determined results from actual field measurements of leak incidences were used to validate the results. The result determined from the model developed proved accurate with only an average error of 0.216 miles.

Keywords: Fluid transport; pipeline modeling; field measurements; hydraulic parameters; flowrate monitoring.

NOMENCLATURES

GPUGPC : Graphics Processing Units of General-Purpose Computing
EBLDS : Externally Based Leak Detection Systems
IBLDS : Internally Based Leak Detection System
NPW : Negative Pressure Wave
NPWs : Negative Pressure Waves
MBLDS : Model Based Leak Detection System

1. INTRODUCTION

Pipelines have been of use for the transport of hydrocarbons and its products for centuries. Pipelines present the most economical and efficient means of transporting fluids (hydrocarbons, its products and other fluids) from one place to another. Pipelines have been useful in bridging the gap between energy resource owners and users by making the resource available to end users in distant locations usually far away from areas of production. Despites these accolades, pipelines are not without its inherent challenges: one of these is the occurrence of leaks during pipeline transportation [1,2]. Leak is defined as the unintended loss of material mass from the pipeline through an opening abruptly created along the pipeline body. Leaks can be caused by human, environmental or operational factors, but whichever the case, leaks are undesirable because it translates to great financial losses, operational difficulties and environmental consequences [3,4]. Regulatory frameworks established to minimize the impact of leaks in pipelines focuses on pressuring the pipeline operators to design systems capable of providing means to rapidly detect and localize leak when it occurs. Thus, more recently, leak detection systems have become standardized components of pipeline systems even though improvements in their design and methodologies are needed [5,6]. Leak detection systems play vital roles in the overall integrity and management of the pipeline. Leak detection systems helps in the early detection of leaks. Early leak detection and localization using innovative methods and technologies pays off by allowing sufficient time for safe shutdown of the pipeline system and rapid response of remedial (cleanup and repairs) crews, thus minimizing the volume and impact of the material loss [7]. There are two broad classifications of leak detection systems. These include: those systems that detect leak using the released fluid, and are referred to as externally based leak detection systems (EBLDS) and those systems which detect leak by observing the hydraulic behaviour of the fluid inside the pipeline which is called internally based leak detection system (IBLDS) [8]. The EBLDS otherwise known as physical or hardware leak detection systems, utilize special hardware technologies uniquely engineered to respond to hydrocarbon contact. The EBLDS include: fluid sampling, soil monitoring, flowrate monitoring, and acoustic, optical, and satellite-based hyperspectral imaging. Meanwhile the IBLDS which are also known as software methods or model-based leak detection methods utilize mathematical models usually transformed into computer algorithm and software platforms. These mathematical models are analytically or numerically developed to detect leak in pipelines by solving the governing equations in the pipeline systems and detecting changes in the hydraulic behaviour of the fluid in the pipeline from its original stable signature [9]. These systems include mass balance, pressure balance, pressure waves and real-time transient methods. These methods have been proven to be formidable in detecting with certainty of accuracy, even small degrees of leak [10,11]. Ideally, it has been stated that the several leak detection systems are able to detect leaks of various sizes no matter the application whether liquid or gas [12]. However, in reality, errors in alarms persist and these errors impact on the choice of the methodology or technology of leak detection. It is therefore worth knowing that errors in alarm are critical factors of any leak detection approach when analyzing their performance and strength. Errors in alarm substantially increases the operational cost associated with leak detection systems and significantly impact on their response time, performance and reliability [13,14]. Attempt to model leak detection and location in pipelines have been mostly focused on gas pipelines. Only few studies have focused on liquid pipelines especially crude oil pipelines. This is because of the greater impact posed by the rather volatile and erratic gas resource than oil which makes its detection and modeling an eventful research. Nevertheless it is critical to fully analyze the dynamics of leaks in liquid pipelines as they are common sites in pipeline transport applications and constitutes the commonest pipelines most readily besieged by humans [15,16].

2. LITERATURE REVIEW

Many scholars have worked on leak detection systems. Marriaga [17] reviewed the technological approaches to leak detection. He investigated the best methods for leak detection in pipelines. He demonstrated that leak detection methods are classified based on the type of technology used. He classified leak detection methods that use inferential statistics as predictive approach to leak detection. Isehunwa [18] conducted a study where they classified leak detection system into hardware, software and biological leak detection systems. They classified the leak detection using special sensors such as acoustic, optical and ultrasonic flow meter as hardware methods; they concluded that though these methods are simple and accurate, but their implementation cost is very high and they are immensely susceptible to false alarm and inaccurate predictions. They classified the software methods as those that use the principle of mass balance, pressure wave, thermal and numerical methods while the biological methods are those that uses animals such as trained dogs for the detection of leak. Akinsete [19] conducted a research on leak detection systems in natural gas pipelines using observer design technique. They treated the leak detection problem as a regress-classification hierarchical problem where the intelligent model (machine learning approach) they proposed act as a regression and a leak detection algorithm act as a classifier. They made comparison between the intelligent model and real-time transient model (RTTM) and observed more accuracy in results from the former. Garcia-Hernandez [20] worked on leak detectability in an offshore multiphase production system. They simulated a leak condition in the middle of a trunk-line to investigate the effect of the hydrodynamics of the system and the ends of the facility. They used different gas-oil-ratio and pipeline pressures to evaluate the effect of these conditions on leak detectability. They suggested that for leak detection, there should be provision to differentiate between the leak detection signals from the normal pipeline noise as detected by the alarm. Mracka [21] used massive parallelization on graphics processing units of general-Purpose computing (GPUGPC) to localize leak. The method involves solving an inverse problem to a simulation of a gas flow immediately following a leak occurrence. The method combines both software and hardware techniques. Their result was precise, fast and robust. Nicholas [22] reviewed RTTM by highlighting the factors of value for effective gas pipeline leak detection and examining the impact of leak detection and location sensitivity. Mookonil [5] researched on leak detection system on pipeline gas distribution. They suggested that PLDs is a significant preventive maintenance tool. They presented viable technology with comparative analysis of its performance indices and limitations. Jin [23] worked on leak detection in pipelines using negative pressure wave (NPW) technique. He investigated the parameters that affect the performance of NPW in pipeline system for leak detection. He established numerical tests based on data sets generated from a hydraulic simulation tool. He used different leak cases to investigate the impact of various parameters on the estimation of leak location, noise level, data acquisition, leak location wave speed etc. Reynolds [24] conducted a study on NPW in pipelines, and they evaluated the challenges, limitations and uses of NPW leak detection. They conducted their investigation using two different pipelines. They discovered that the leak detection worked more effectively on smaller pipeline segments running in steady state, and that more accurate leak location as well as fewer false alarms, and very fast detection times were obtained. They concluded that NPW technique yields fast detection of leaks due to the high speed of travel of the NPWs used as the factor of leak detection.

2.1 Model Based Leak Detection and Localization Systems

In actual sense, leak detection and localization are distinct from each other. A leak detection system basically is a system designed to identify a leak which triggers the alarm system. The alarm system notifies the pipeline monitoring team that a leak has occurred and immediate remedial actions are commenced. On the other hand a leak localization system The principal model-based leak detection methods are outlined and discussed herein is one that locates the position along the pipeline system where the leak has occurred. While some systems designed for leak management systems comprise both the detection and localization of leak, most are only able to detect the leak and are not able to spot the location on the pipeline length where the leak occurred [3,25,26]. Model based leak detection system (MBLDS) otherwise known as software based or IBLDS utilize models written as algorithms that are implemented in a computer software module. The algorithms consistently monitors the state of pressure, temperature, flowrate or other pipeline hydraulic parameters and can detect changes in the trends of these properties from the established trend in stable no leak conditions. When leak occurs there is perturbation created by the leaking fluid to the environment that distorts the normal established trend of these pipeline hydraulic parameters and these changes being detected and conformed to be leak triggers the alarm system. However, it is crucial to note that the complexity and reliability of these software packages vary significantly. Intuitively software leak detection system relies on flowrate/pressure change, mass/volume change or dynamic model-based systems. MBLDS is usually part of the supervisory control and data acquisition (SCADA) unit for pipeline monitoring and control [7,26]. In all the literatures reviewed, none was on MBLDS with the incorporation of graphical user interface (GUI) on crude oil pipeline. In this work, MBLDS with GUI on crude oil pipeline was developed and simulated. The modeling was done by modifying the Darcy-Weisbach and Bernoulli equation of fluid flow in pipelines by developing suitable equations that estimates the exact distance along the length of the pipeline where the leak has occurred. Thus, not only will the model detect the leak but also estimates the exact distance along the pipeline length where the leak occurred.

3. METHODS

The methods comprise the following

1. The development of leak detection model
2. The development of leak localization model

The sequence of methodology is given in the block diagram in Fig. 1.

3.1 Leak Detection Model Development

The leak detection model is developed using mass balance method. This method uses the principle of conservation of mass in the pipeline system. For steady state the mass rate into the pipeline is equal to the mass rate out of the pipeline. This remains the case when there is no leak as the mass accumulation translates to zero. The following assumptions were considered in modeling the leak detection in the pipeline:

i. The temperature of the pipeline is assumed to be uniform throughout the entire length of the pipeline

ii. The pipeline is assumed to be in constant elevation throughout its length (i.e. to say no changes in elevation).

iii. The fluid in the pipeline is single phase liquid (i.e. crude oil)

iv. The pipeline is on the surface and not buried so there is no geothermal temperature effect on the pipeline

Fig. 2 is a diagrammatic representation of pipeline carrying crude oil when there is no leak. The pipeline runs from point 1 to point 2. The pressure at the upstream (inlet point) of the pipeline at pint 1 is P_1 while the pressure at the downstream (delivery point) of the pipeline at point 2 is P_2. The crude oil flows from point 1 to point 2. Under steady state condition, when there is no leak, the net mass accumulation in the pipeline is zero (continuity equation) as given by equation 1.

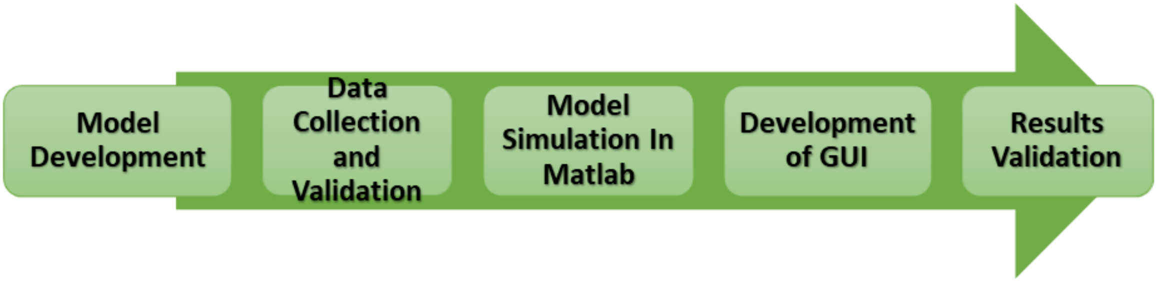

Fig. 1. Sequence of methodology

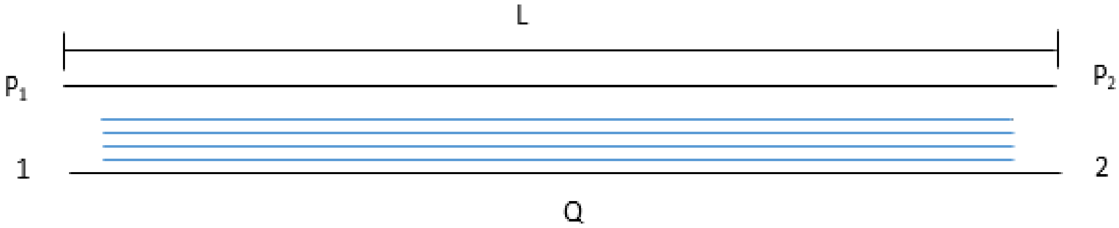

Fig. 2. Pipeline condition for no leak

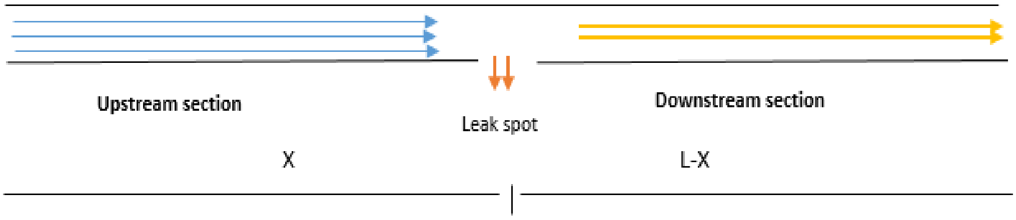

Fig. 3. Pipeline schematics for determination in the presence of leak

$$M_{in} - M_{out} = 0 \tag{1}$$

Equation 1 is expanded to become

$$\rho_1 A_1 U_1 - \rho_2 A_2 U_2 = 0 \tag{2}$$

Where: $\rho_1 A_1 U_1$ - mass in and $\rho_2 A_2 U_2$ - mass out, with U_1 and U_2 as volumetric velocities, ρ_1 and ρ_2 as fluid densities

On event of leak in the pipeline, the algebraic sum of the mass flow rate is not equal to zero but equal to the mass flowrate due to leak

$$M_{in} - M_{out} = M_{leak} \tag{3}$$

Equation 3 can be written in expanded form as

$$\rho_1 A_1 U_1 - \rho_2 A_2 U_2 = \rho_L A_L U_L \tag{4}$$

Equation 4 is a one-dimensional steady state continuity equation. It is useful in monitoring of fluid flow in pipelines and detection of leaks. If the recorded flowrate differs from the expected flowrate, the alarm system is triggered and it may be due to a leak. From the steady state isothermal horizontal pipeline in Fig. 1, the pressure required for the flow from point 1 to point 2 is given by the frictional losses which create pressure drawdown along the pipeline. The flow is made possible from the inlet by use of centrifugal pumps. Elevation effects in the pipeline are negligible since the pipeline has been assumed to be horizontal. The fluid flows throughout the pipeline from inlet at point 1 to the outlet at point 2 with steady uniform flowrate.

Consider the pipeline in Fig. 3. Due to leak, the pipeline has been sectioned into three distinct regions. The first section is the upstream section of the pipeline and begins from the inlet of the pipeline to the point of leak occurrence. The mid-stream section covers the entire diameter of the leak opening while the downstream section begins from the leak point to the delivery point of the pipeline. Thus, the upstream section borders the region from $x = 0$ to $x = x_l$. The midstream section is a singularity point at the point of leak while the downstream section is the region from $x = x_l$ to $x = L$.

3.2 Leak Localization Model Development

To localize the leak, mathematical model is developed using Darcy pressure loss equation in pipeline. Development of the equations are done for pipeline fluid flow in the absence of leak and for pipeline fluid flow subject to leak

3.2.1 Leak localization model for upstream section of the pipeline

The equation for pressure loss (ΔP) in a liquid horizontal pipeline is given as:

$$\Delta P = 0.0605 \frac{fLQ^2(SG)}{D^5} \quad (5)$$

Making Q the subject of the formula

$$Q = \left(16.5289 \frac{\Delta P D^5}{fL(SG)}\right)^{0.5} \quad (6)$$

Equation 6 is further simplified to get

$$Q = 4.0656 \left(\frac{\Delta P D^5}{fL(SG)}\right)^{0.5} \quad (7)$$

Equation 7 is the equation for liquid flowrate in a liquid pipeline.

Equation 7 can be further simplified as

$$Q = K\Delta P^{0.5} \quad (8)$$

$$Q = K(P_1 - P_2)^{0.5} \quad (9)$$

Where: P_2 − outlet pressure, (psia), P_1 − inlet pressure (psia), f – Fanning friction factor, Q – gas flowrate (ft3/hr), SG – gas specific gravity, L – Pipeline length (miles), D – pipeline diameter.

K represents the other pipeline fluid flow parameters in Equation 7. K also represents the constant of proportionality for a fluid flow in liquid horizontal pipeline when there is no leak. As the fluid flows from inlet to the discharge point downstream of the pipeline, pressure drop occurs in the pipeline due to the effects of frictional forces in the pipeline. These frictional forces are due to the roughness of the pipeline.

$$K = 4.0656 \left(\frac{D^5}{fL(SG)}\right)^{0.5} \quad (10)$$

Equation 10 is used to determine the pressure profile in a liquid horizontal pipeline when there is no leak. This is the normal pipeline pressure profile when there is no leak and each pipeline has a pressure profile signature defined by Equation 10 prior to leak. The occurrence of leak alters this established pressure profile. A pressure sump is quickly notice just at the point of leak and reduces the pipeline flowing pressure at that point. This pressure reduction tries to normalize by building up with time as the fluid flow continues. The rate of buildup of the pressure to normalize is dependent on the size of the leak opening and the pressure of the escaping fluid from the leak opening. The pressure sump created by the leak opening creates another pressure profile in the pipeline different from the one established when the pipeline was flowing without leak. If we consider the upstream section of the pipeline when there is no leak (i.e. region $0 \le x \le L$.), the pipeline fluid flowrate (Q_{up}) is represented as

$$Q_{up} = K_{up}(P_1 - P_L)^{0.5} \quad (11)$$

Then, $\mathrm{K_{up}}$ becomes:

$$\mathrm{K_{up}} = 4.0656 \left(\frac{D^5}{fX(SG)}\right)^{0.5} \quad (12)$$

X in the Equation 12 denotes the leak localization point with SG – specific gravity. Because the upstream section occurs prior to the region of leak, the fluid flowing in the upstream section flows undisturbed until it reaches the point of leak. In this upstream section, the pipeline flowing fluid maintains its speed much the same manner as a pipeline flowing in the absence of leak. The ratio of the pipeline fluid flowrate when there is absence of leak and the pipeline fluid flowrate during leak is represented as:

$$\frac{Q}{\mathrm{Q_{up}}} = \frac{K(P_1 - P_2)^{0.5}}{K_{up}(P_1 - P_l)^{0.5}} \quad (13)$$

This can also be written as

$$\frac{K}{\mathrm{K_{up}}} = \frac{Q(P_1 - P_L)^{0.5}}{Q_{up}(P_1 - P_2)^{0.5}} \quad (14)$$

Putting Equation 13 into Equation 14 yields

$$\frac{4.0656\left(\frac{D^5}{fL(SG)}\right)^{0.5}}{4.0656\left(\frac{D^5}{fX(SG)}\right)^{0.5}} = \frac{Q(P_1 - P_L)^{0.5}}{Q_{up}(P_1 - P_2)^{0.5}} \quad (15)$$

Evaluating Equation 15 gives

$$\frac{1/_{L^{0.5}}}{1/_{X^{0.5}}} = \frac{Q(P_1-P_L)^{0.5}}{Q_{up}(P_1-P_2)^{0.5}} \tag{16}$$

Simplifying equation 16 gives

$$\frac{X^{0.5}}{L^{0.5}} = \frac{Q(P_1-P_L)^{0.5}}{Q_{up}(P_1-P_2)^{0.5}} \tag{17}$$

Squaring both sides of Equation 17 and making X the subject of the formula gives

$$X = \left(\frac{Q}{Q_{up}}\right)^2 \frac{(P_1-P_L)}{(P_1-P_2)} L \tag{18}$$

Equation 18 is the equation for leak localization in the crude oil pipeline. A good leak localization determination depends on the accurate estimation of the pressure at the point of leak (P_L)

3.2.2 Leak location model for downstream section of pipeline

When leak has occurred, the pipeline fluid flowrate in the downstream section (Q_d) of the pipeline is given as:

$$Q_d = K_d(P_L - P_2)^{0.5} \tag{19}$$

K_d denotes

$$K_d = 4.0656\left(\frac{D^5}{f(L-X)(SG)}\right)^{0.5} \tag{20}$$

A comparison of Equation 9 and Equation 19 yields

$$\frac{Q}{\mathrm{Q_d}} = \frac{K(P_1-P_2)^{0.5}}{K_d(P_L-P_2)^{0.5}} \tag{21}$$

Equation 21 can further be represented as:

$$\frac{K}{\mathrm{K_d}} = \frac{Q(P_L-P_2)^{0.5}}{Q_d(P_1-P_2)^{0.5}} \tag{22}$$

Putting Equation 21 into Equation 22 yields:

$$\frac{4.0656\left(\frac{D^5}{fL(SG)}\right)^{0.5}}{4.0656\left(\frac{D^5}{f(L-X)(SG)}\right)^{0.5}} = \frac{Q(P_L-P_2)^{0.5}}{Q_d(P_1-P_2)^{0.5}} \tag{23}$$

Evaluating Equation 23 gives

$$\frac{(L-X)^{0.5}}{L^{0.5}} = \frac{Q(P_L-P_2)^{0.5}}{Q_d(P_1-P_2)^{0.5}} \tag{24}$$

Squaring both sides of Equation 24 and simplifying gives:

$$L - X = L\left(\frac{\boldsymbol{Q}}{\boldsymbol{Q_d}}\right)^{\boldsymbol{2}} \frac{(\boldsymbol{P_L-P_2})}{(\boldsymbol{P_1-P_2})} \tag{25}$$

Making X the subject of formula gives:

$$X = L - L\left(\frac{\boldsymbol{Q}}{\boldsymbol{Q_d}}\right)^{\boldsymbol{2}} \frac{(\boldsymbol{P_L-P_2})}{(\boldsymbol{P_1-P_2})} \tag{26}$$

This can be factorized to be

$$X = L\left(1 - \left(\frac{Q}{Q_d}\right)^2 \frac{(P_L-P_2)}{(P_1-P_2)}\right) \tag{27}$$

Equation 27 is the equation for leak localization in the pipeline from the downstream section of the pipeline

3.3 Simulation

The model was built into computer software and used for simulation and analyses. The model simulation sequences are: Data collection, Data accuracy determination, Matlab Simulation and finally result presentation.

3.3.1 Data collection

The pipeline fluid flow and leak data used for simulation in this work depicted in Table 1 are gotten from ABX Oil Company operating in the Niger Delta region of Nigeria. Most of the data were collected by hand from the company while some were sourced from the company's database online. The sourced data were then fed into the model simulator designed in GUI.

3.3.2 Determining accuracy of data

Data validation done in Matlab was used to determine the accuracy of the input data. This was done by coding a test script and running it to see if the input pipeline parameters would yield the desired pressure drop in the pipeline. The pressure drop is the difference between the inlet and outlet pressures of the pipeline. Darcy-Weisbach pressure drop equation was used to achieve this. If the calculation done using equation 5 equals the pressure drop in the pipeline, then the pipeline input parameters are accurate, and vice versa. Not validating the data could bring in errors into the model results.

Table 1. Input data used for the simulation

Parameter	Values			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Pipeline Length, L (miles)	50	62	60	120
Pipeline Internal diameter, D (inch)	16	16	14	24
Inlet pressure, P_1, (psi)	906	1106	932.27	1091.27
Outlet Pressure, P_2 (psi)	200.5	150	180	200
Fluid temperature t, of	100	100	100	80
Base temperature, T, of	60	60	60	60
Pressure at the point of Leak, P_L (psi)	557	765	441	657
Pressure downstream of leak point P_d, (psi)	420.4	555.5	257.4	312.8
Viscosity of the fluid, (cp)	0.4	2	0.53	0.6
API gravity	37.1	26	36.55	36.2
Pipe absolute roughness, e (inch)	0.0016	0.0018	0.0012	0.0022
Flowrate in no Leak situation, Q (b/d)	150000	140000	100000	300000
Flowrate Upstream of pipeline during leak, Q_L (b/d)	150000	140000	100000	300000
Flowrate downstream of pipeline during leak, Q_d (b/d)	145550	135350	92300	291425

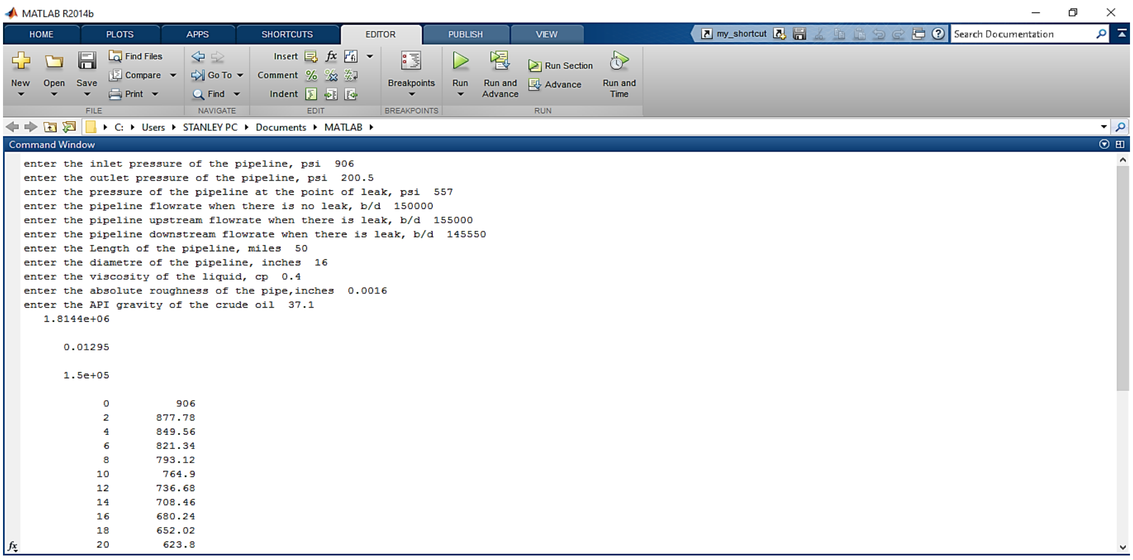

Fig. 4. Matlab calculation result window

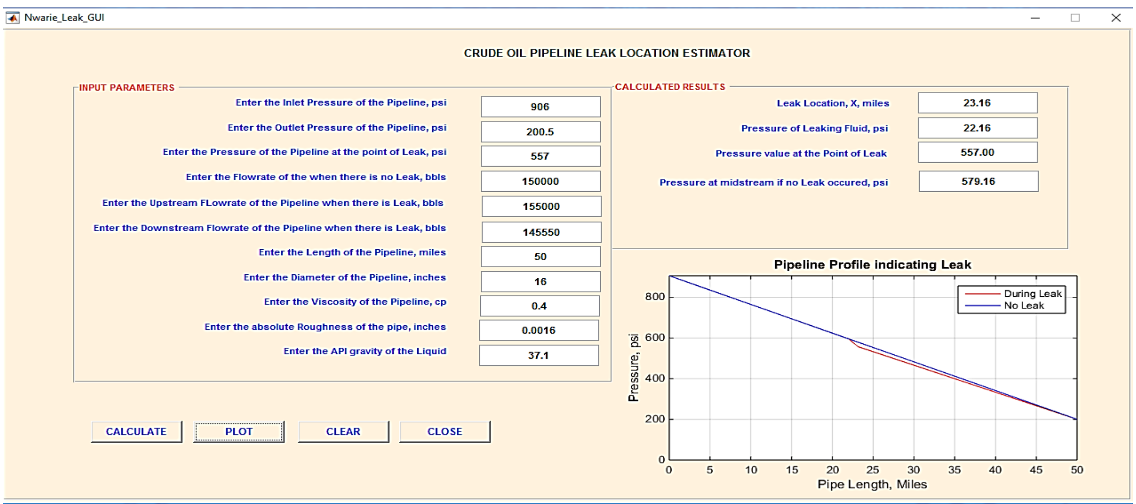

Fig. 5. Crude oil pipeline leak location estimator (Matlab GUI)

3.3.3 Matlab simulation

The software used for the simulation in this work is Matlab R2014b. Matlab is robust software for scientific and engineering simulations. It offers users the environment to code and write executable scripts which can be run on the command window or in graphical user interface (GUI). Matlab makes it possible for engineers to run optimizations on models through its specially-built toolboxes. In this work, the simulation done in Matlab was done for leak localization determination and pressure at the point of leak determination. Results from Matlab simulations displayed in Fig. 4 were imported to Excels spreadsheet application for visual representation (charts and graphs) because of Excel's enhanced graphics features. Matlab's GUI, Fig. 5 was developed to enable quick computation and determination of leak localization and pressure at the point of leak upon leak occurrence in the pipeline.

The GUI helps users to easily estimate the location of leak in a simple user friendly manner. The input parametres are the pipeline hydraulics parameters. When the input variables are inserted in the spaces accordingly, the CALCULATE button is clicked and the calculated results are displayed immediately on the calculated result pane. The PLOT button displays the graphical representation of the pipeline profile for the pipeline for the 'leak case' and the 'no leak case' on the same graph. The plot further depicts the scenario of leak with a pressure decrease at the location of leak. The clear button clears old variables and information in readiness for new input. The close button closes the GUI and the entire Matlab software. The GUI named Leak_Locator.m can be made commercial and sold to pipeline operators to help in on the spot leak location in crude oil pipelines.

4. RESULTS AND DISCUSSION

The results from the study carried out are presented below. The results comprise the leak location, the pipeline pressure gradient profile, the pressure at the point of leak and the downstream pressure profile. Comparison is made between results from model and results from actual field cases.

4.1 The Leak Location

Table 2 depicts the results of simulations for the leak location. From Table 2, the leak occurred at 23.164 miles from the inlet for case 1, at 19.265 miles for case 2, at 35.54 miles for case 3 and at 54.652 miles for case 4. The model results falls within pipeline length range as no leak location results were greater than the pipeline length considered. From Table 2, the pressures at the leak locations are: 557 psi at 23.164 miles for case 1, 765 psi at 19.265 miles for case 2, 441 psi at 35.54 miles for case 3 and 657 psi at 54.652 miles for case 4. To analyze the accuracy of the results obtained from the model, the work of Jin [23] was used. Jin used the method of NPW to determine the leak location. According to him, pressure waves are created when leak occurs that travels upstream and downstream of the pipeline at a certain speed. With pressure transducers placed at strategic points on the pipeline, the waves can be detected and the time it was detected analyzed, and with the reference points where wave detectors are placed, the location of leak (apparently where the waves emanated from) can be detected. The difference between the results from the developed model and the work of Jin [23] gives an average error difference of only 0.216 miles. This corresponds to a percentage error difference of 0.7% for the four cases considered.

4.2 Pressure at the Point of Leak

As earlier stated, the determination of the leak localization and its accuracy depends on how the pressure at the point of leak, and from the simulation performed with results presented in Table 2, the pressure at the point of leak is 557 psi at 23.164 miles for case 1, 765 psi at 19.265 miles for case 2, 441 psi at 35.54 miles for case 3 and 657 psi at 54.652 miles for case 4.

Table 2. Results of simulations for leak location

Parameter	Simulation Results			
	Case 1	**Case 2**	**Case 3**	**Case 4**
Pipe friction factor	0.0130	0.0152	0.0132	0.0129
Leak Location, Miles	23.164	19.265	35.540	54.652
Pressure at the point of Leak, PL (psi)	557	765	441	657

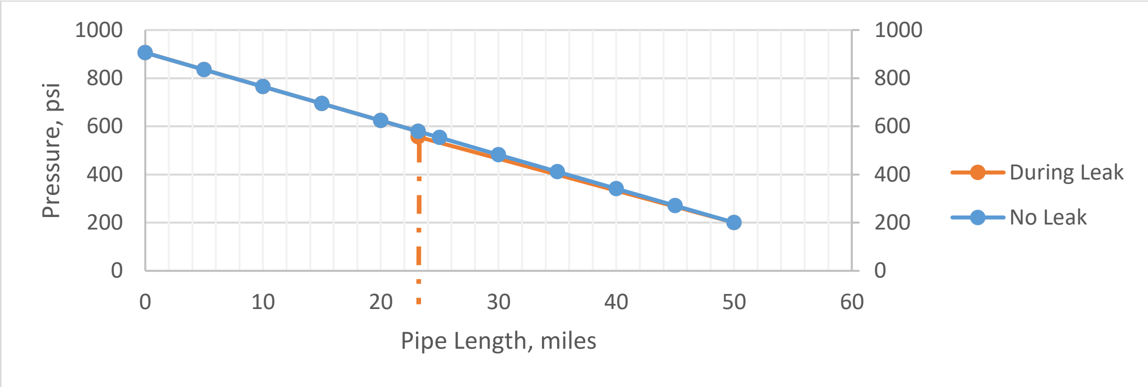

Fig. 6. Pressure profile for case 1 during leak and in the absence of leak

4.3 The Pipeline Pressure Profile

The pressure profile for the pipeline for each case is presented below.

Case 1: The pipeline pressure gradient plot for case 1 is given in Fig. 6. Fig. 6 depicts Pressure gradient profile for case 1 pipeline in the absence of leak and during leak. Notice from Fig. 6 that the pressure profile for the pipeline for the no leak is a straight-line with constant gradient. The pipeline in the no leak condition continues with this pressure gradient until perturbation is induced in the pipeline. With the pressure gradient, it is possible to predict the flowing pressure at any point along the length of the pipeline from inlet to outlet. From the figure, the pressure gradient profile for the pipeline prior to leak is a straight line with slope equal to the pressure drop per unit length of the pipeline. This straight line is maintained for the pipeline only to be altered due to leak. When Leak occurs there is a sharp decrease in pressure leading to a deviation from the established pressure gradient profile for this pipeline. This reduction in pressure at the leak point is shown by the red dotted line in Fig. 6. The dotted line signifies the point of leak where there is a sharp decrease in pressure. Leak occurrence creates instantaneous perturbation on the pipeline hydraulics that results in the immediate decrease in the pipeline pressure at the point of the leak. The leak travels downstream as shock waves. The waves become less severe as the pipeline system tries to adjust to annul the effect of the shock. The level of reduction in pressure at the point of leak is largely governed by the diameter of leak opening, the velocity of fluid flow at the point where leak occurred just before the leak was induced and the rheological properties of the flowing fluid. From Fig. 6, leak occurrence created another pressure profile with less pressure gradient than that for no leak case. Furthermore, from the leak point, the pressure profile affected by leak intersects the pressure profile for no leak. At this point the pipeline pressure profile has normalized and from the point of normalcy, the pressure profile downstream is as if there was no leak. From Fig. 6, it can be observed that the leak occurred at distance of 23.164 miles from the point of inlet. This is equivalent to distance of 37.28 km from the inlet point. To verify the accuracy of the model result, comparison is made with the work of Jin [23] using same input data. From the work of Jin [23], the distance of leak was determined to be at a distance of 23.36 miles. The error difference between the developed model and that of Jin [23] is 0.196 miles (0.315km). It can be seen that the model developed herein is comparable to the work of Jin [23] which was acceptable with a percentage deviation of 0.86%. Again, it can be observed from Fig. 7 that the leak profile line intersected the no-leak line at distance of 45 miles. This means that the leak effect was felt between 23.164 miles and 45 miles, a distance of 22.164 miles. Beyond 45 miles of the pipeline, the pressure has normalized and the effect of the leak was no longer felt.

Case 2: The pipeline pressure gradient plot for case 2 is given in Fig. 7 and also depicted in Fig. 7 is the pressure gradient for case 2 pipeline in the absence of leak and during leak. Notice from Fig. 7 that the pipeline has a straight-line pressure profile with constant gradient. The pipeline in the no leak condition continues with this pressure gradient until perturbation is induced in the pipeline. With the pressure gradient, the flowing pressure can be predicted at any point along the pipeline length from inlet to outlet. During leak, the pressure drops at the point of leak with an indication of this shown by red the dotted line. Thus, leak incidence created a new hydraulic pressure gradient given by the red line and continues from leak point to pipeline exit. In the downstream section, there is pressure reduction from the pressure predicted for the normal pipeline operation in the absence of leak. From Fig. 7, it can be observed that the leak occurred at a distance of 19.27 miles (31 km) from the point of inlet. The created leak pressure profile due to leak incidence was visible from 19.27 miles to 55 miles and was felt at 35.73 miles of the pipeline length with pressure normalization occurring at 55 miles. The leak pressure profile normalization point intersected the no-leak pressure profile at 55 miles of the pipeline length. Verification of the model result was carried out by comparison with the work of Jin [23] using same data. Result obtained indicated that Jin [23] had distance of leak at 19.41 miles. The error difference between the developed model and that of Jin [23] is 0.14 miles (0.23km) with percentage deviation of 0.72% as seen in Table 3. Thus, model developed in this study has high acceptable level of accuracy.

Case 3: Fig. 8 shows the pressure gradient established for the pipeline in the absence of leak and during leak for case 3. This pressure profile is altered during leak. There is a sharp drop in pressure as can be observed in Fig. 8 at a distance 35.54 miles from the inlet point of the pipeline. This is the point of leak occurrence creating pressure sink at the leak point with a slope lower than that established for the no-leak case. The leak pressure profile runs from 35.54 mile to 58 miles. Thus the pipeline pressure profile after leak, normalized at 58 miles. The effect of leak was felt between 35.54 miles and 58 miles. From Fig. 8, it can be observed that the leak occurred at distance of 35.54 miles or 57.20 km from the point of inlet. Verification of model result accuracy was done by comparison with Jin [23] work using same input data (Table 3). From Table, Jin [23] had leak at 35.28 miles. The error difference between the developed model and Jin [23] is 0.26 miles (0.42km) with percentage deviation of 0.74%.

Case 4: Given in Fig. 9 is the pipeline pressure gradient plot for case 4. For case 4, the length of the pipeline is 120 miles with pressure profile deviating from normal pipeline pressure signature at approximately 54.65 miles from the inlet point. This point is known as the leak location in the pipeline. Fig. 9 depicts both the profile for leak and the absence of leak. From Fig. 9, it can be observed that the leak occurred at distance of 54.65 miles, which corresponds to 87.95 km from the inlet point. Verification model result accuracy was done by comparison of Jin [23] work with same data. From the work of Jin [23], the distance of leak stood at 54.39 miles. The difference between the developed model and that of Jin [23] is 0.26 miles (0.42km) with a percentage deviation of 0.48% as seen in Table 3. Thus, the leak location model developed in this study again gives result with acceptable accuracy.

4.4 Pressure of the Leaking Fluid

The pipeline fluid exits the pipeline at the leak opening with a pressure equal to the difference between the original pressure at the distance where leak occurred when the pipeline was flowing without leak and the pressure at the leak point during leak occurrence. This difference in pressure is known as the pressure of the leaking fluid. This can be estimated from the pipeline pressure gradient chart when the pressure gradients of the pipeline without leak and during leak are plotted together. The calculated differences in pressure depicted in Table 4 are the pressures of the leaking fluid. The pressures of the leaking fluid from Table 4 are 22.16 psi, 43.96 psi, 45.67 psi and 27.56 psi for case 1, case 2, case 3 and case 4 respectively. The pressure of the leaking fluid is the hydraulic force that pushes the fluid out of the pipe through the leak opening. The flowrate of the leaking fluid is

Table 3. Comparison of results from model developed in this study with that of Jin [23]

Case	Leak location from developed model (miles)	Leak location from Jin [23], (miles)	Difference, (miles)	% Deviation
1	23.164	23.36	0.196	0.86%
2	19.265	19.41	0.145	0.72%
3	35.54	35.28	0.260	0.74%
4	54.652	54.39	0.262	0.48%

determined by material balance in the pipe for no leak and leak case. It can be observed that case 3 has the highest leaking fluid pressure. Thus, more fluid escaped per unit time from case 3. The leak flowrate so determined can aid in the estimation of the diameter of the orifice, given the pressure of the leaking fluid. This can be achieved by equating the pressure drop calculated herein to that of an orifice, assuming the leak opening to be an orifice.

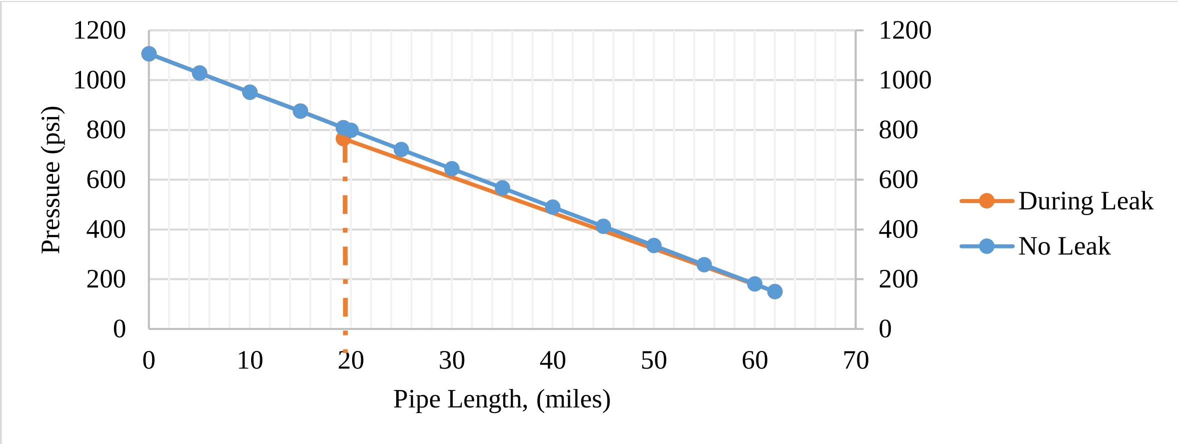

Fig. 7. Pressure profile for case 2 during leak and in the absence of leak

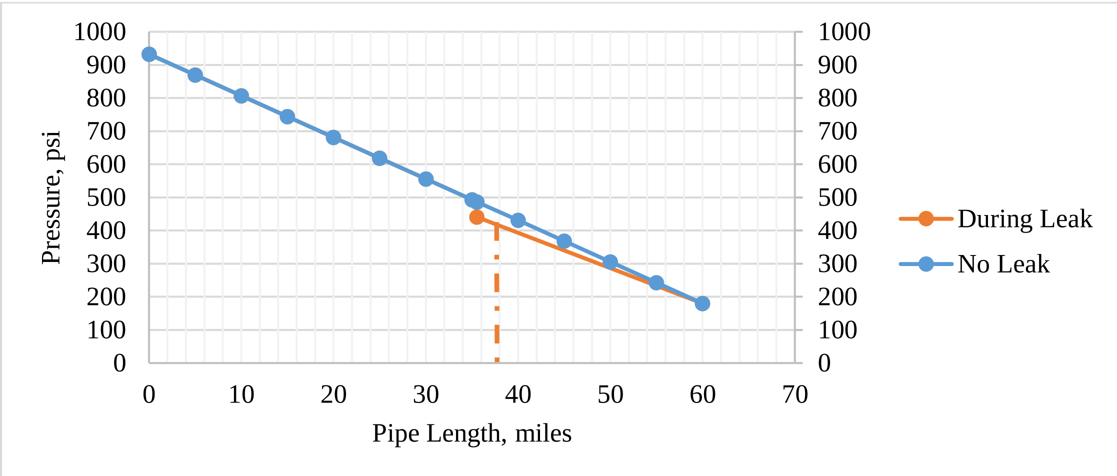

Fig. 8. Pressure profile for case 3 during leak and in the absence of leak

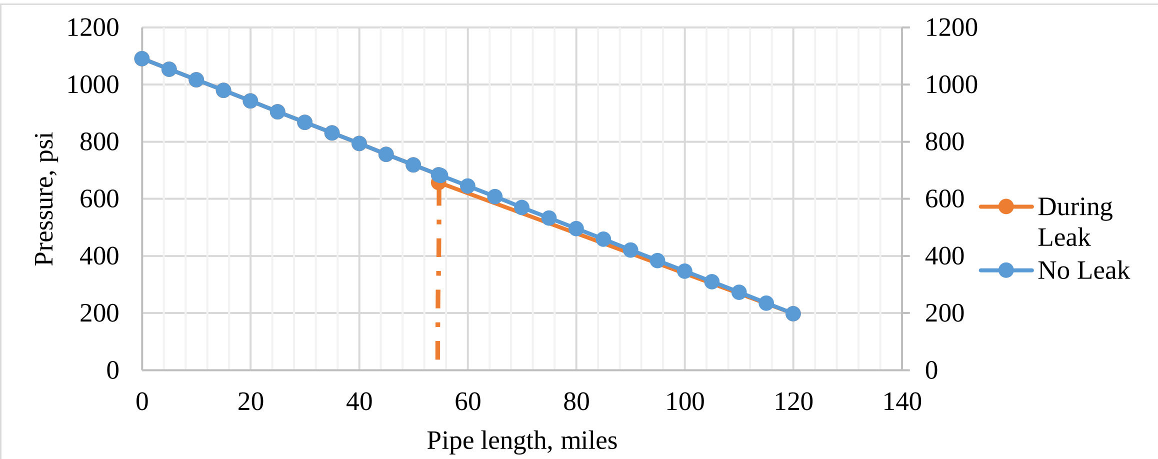

Fig. 9. Pressure profile for case 4 during leak and in the absence of leak

Table 4. Pressure difference at the Leak Point

Case	Leak distance, miles	Estimated Pressure for no leak, psi	Pressure at leak point during Leak, psi	Difference in pressure, psi
1	23.164	579.16	557	22.16
2	19.265	808.96	765	43.96
3	35.54	486.67	441	45.67
4	54.652	684.56	657	27.56

5 CONCLUSIONS

In this study, Leak location model have been developed analytically for the estimation of the location of leak in pipelines. The model was able to not only determine, detect and localize the leak accurately but also estimated the pressure at that point of leak in the pipeline. From the study, the following conclusions are drawn:

i. The pressure of the pipeline at a certain point before leak is always higher than the pressure of the pipeline during leak at that same point. This is as expected and indicates the accuracy of the model

ii. Due to leak, the fluid flowrate in the pipeline increase in the upstream section of the pipeline and decreased in the downstream section. This is in agreement with literature.

iii. The pressure of fluid exit from the leak opening equaled in all cases the difference between the pipeline pressure at that point before and during leak

iv. The obtained results compared acceptably well with the work of Jin [23] that used NPW approach. The obtained results are within the acceptable tolerance for leak location in pipelines.

v. Generally, the leak occurrence reduced the pressure of the pipeline at the leak point leading to fluid exit out of the pipeline. This automatically increased the flowrate upstream of the pipeline and reduced the flowrate downstream of the pipeline.

vi. The developed Leak location model in this study detected the leak location for the four cases considered with the corresponding pressures at the point of leak location. It went further to estimate the pressure of the leaking fluid from the pipeline ruptured exit point.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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