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Research Article

Transient Model-Based Leak Detection and Localization Technique for Crude Oil Pipelines: A Case of N.P.D.C, Olomoro

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Abstract: This work presents the fundamentals and application of transient model-based leak detection and localization technique for crude oil pipelines. The dynamic parameters involved in this model such as pressure, flow and temperature were acquired by SCADA (Supervisory Control and Data Acquisition) system. The characteristic changes in the flow-mechanics and thermodynamics along a given length of pipeline were used in detecting, localizing and determining the flow rate of the leak. Measurement of pressure, temperature and flow data at both the inlet and outlet of the pipeline were used in formulating the equations obtained from the inconsistency in the continuity and law of conservation of momentum equations. This model located a leak incident in a horizontal pipeline of length 2000m and diameter 0.3556m carrying Nigeria bonny light crude oil from the Nigeria Petroleum Development Company Limited, Olomoro flow-station into UPS (Ughelli Pump Station) truck line. But the leak located by the model at 1088.12m from the inlet is 11.88m behind the actual leak position of 1100m as discovered during the pipeline leak remedial works.
Keywords: Transient, Leak Detection, Localization, Pipeline, inlet, outlet, SCADA.

INTRODUCTION

Background of the Study

Nature does not provide matter in the shapes, quantities and locations we want them in. Therefore man, in his quest to create products to satisfy his needs for a better and higher standard of living, has to cause a disorder to reorder matter. To create order to reorder matter, work is to be done and energy is needed; consequence of the thermodynamics' law. Crude oil exploration is an example of matter provided by nature which man has to reorder. Crude oil is an important source of energy that is being produced from oil bedrocks or reservoirs. The need to transport crude oil from point of production to area of end use has led to a rapid increase in the number of pipelines being designed and constructed [9]. Pipelines are media required for the transportation of crude oil from reservoir, wellbore and other stations to be delivered to destination point such as separator, storage tanks etc., [17]. Until crude oil is converted into useful products, there are intermediary processes that require one or more unit operations which will involve linkages with one another with the help of pipelines.

Transportation of crude oil in pipelines requires monitoring to detect malfunctioning such as leaks[13]. Over time in operation, these pipelines due to ageing, corrosion and wear, design faults, operation outside design limit or deliberate damage in act of vandalism etc. are caused to leak [17]. Pipeline rupture makes sudden change in pressure, causing economic and environmental problems without detecting the leakage position and repairing in time [20]. Crude oil is in some sense hazardous. It is therefore often necessary to install leak detection (and localization) systems (LDS). Due to the vast pipeline network throughout the country, it is essential that reliable leak detection systems are used to promptly establish a leak, locate its position and estimates its flow rate so that appropriate response actions are initiated in accordance. The celerity of these actions can help mitigate the consequences of accidents or incidents to the people, environment, Assets and reputation of the petroleum industry or the entire country at large. Leak detection systems that have the ability of locating the position of the leak are mainly environmental in nature. But the economical aspect of it cannot be neglected or written off. In fact, pipeline leaks are also frequent problems to the producers and transporters of these hydrocarbons and failure to detect it can result in loss of life and facilities, direct cost of loss product and lie downtime, environmental cleanup cost and possible fines and legal suits from habitants [17].

Instrumentation in the petroleum industry is usually limited to the inlet and outlet of pipelines, only

[13]. This calls for sophisticated signal processing methods to obtain reliable detection of leaks. Some software-based leak detection methods perform statistical analysis on measurements (black box), while others incorporate models based on physical principles [13]. With the use of SCADA (Supervisory Control And Data Acquisition) system on crude oil pipelines, we are able to obtain the dynamic parameters such as pressure, flow and temperature; involved in this model. Generally, some Leakage detection technologies include the following methods [16], the volume-mass balance method, the pressure monitoring method with statistical analysis and/or pattern matching, acoustic monitoring method, the transient leakage detection method, etc. However, many methods are hedged in with their shortcomings, which are, long response time, and incidence of false alarm reporting, etc., [1, 2]. The transient leakage detection is used to monitor whether pipeline is in a normal state by establishing the accurate pipeline model and utilizing perfect numerical methods [20]. Comparatively speaking, the transient leakage detection method has the advantages of speediness and exactness [20].

Statement of the Problem

Over the years, there has been series of catastrophic effects ranging from minor lost time injuries, ill health, loss of containment, damage to property, casualties to major top events such as fire/explosions, loss of lives and property, multiple fatalities and deaths [14][10] in the oil and gas industry in general and in the Nigerian Petroleum Development Company (NPDC) oil and gas facility, Olomoro in particular. The root cause of all these is pipeline leakage due to ageing, corrosion and wear, design faults, operation outside design limit or deliberate damage in act of vandalism etc [17]. The result is oil spillage that causes environmental pollution, destruction of the ecological activities, natural and artificial resources etc; and when met with ignition sources causes fire explosions which could results to death and other multiple fatalities. There is usually late leak detection and localization in the oil and gas industry in Nigeria generally and in the Nigeria Petroleum Development Company Limited (NPDC), Olomoro field particularly. This is as a result of the fact that the 24hr surveillance and perambulation method of leak detection and localization adopted by the petroleum industry is inefficient and non-effective. More also, instrumentation in the petroleum industry is usually limited to the inlet and outlet of pipelines,only[13] making it difficult to detect the intermediate anomalies such as leak. This calls for a dependable leak detection system that will enable leakages to be detected on time.Sophisticated technologies are still rare in Nigeria. Hence a model suitable for the present level of technology in Nigeria to detect, quantify and localize leaks is necessary.

The Aim of the Study

To undertake the modeling of a transient model-based leak detection and localization technique for crude oil pipelines suitable for the present level of technology in Nigeria.

The Objectives of the Study

1. To develop a transient model-based leak detection and localization technique base on the present state of technology in Nigeria.
2. To simulate the model with deviations that occur and the changes in characteristic manner of a particular case scenario.
3. To study the regular data from the inlet and the outlet of a crude oil pipeline and ascertain their behaviour in normal operations.
4. To observe if deviations from regular data obtainable occurs during normal operations.
5. To analyze the deviations that occurs as the data obtainable changes in a very characteristic manner.

The Significance of the Study

Years back, although still in practice, the only means available for crude oil leak detection in pipeline is by perambulation. Recently, leak detection (and localization) systems (LDS) are installed on pipelines transporting hazardous fluids such as crude oil to avoid the dangers or catastrophes pose by such fluids when spilled into the environment. Pipelines must be monitored continuously during operations for the presence of leaks; it is in line with this that on-line monitoring is becoming a routine and in most cases 24 hours surveillance is mandatory [9]. However it is inefficient and ineffective in some cases. Pipeline leaks are frequent problems to the producers and transporters of these hydrocarbons and failure to detect it can result in loss of life & facilities, direct cost of loss product & lie downtime, environmental cleanup cost and possible fines & legal suits from habitants [9, 17]. It is therefore imperative that an efficient and dependable leak detection (and localization) system be put in place.

LITERATURE REVIEW

Leak Detection Systems

Overview

Leak detection and localization systems are installed on pipelines by engineers to protect the environment, lives and property from there percussions of pipelines failure. Whenever a leak occurs, Leak detection and localization systems automatically alerts, signals or notifies the operator by customized alarms, so that necessary steps can be taken to mitigate the quantity of spill and the duration. There are various types of leak detection and localization methods. Some simply identify loss of products (i.e. leak) by the difference between the steady state inventory of the system and the instantaneous inlet and outlet flows [9]. Some others involve the use of complex computer network systems that as well monitor a number of operating conditions. Furthermore, some methods fall in between these two categories in different stages of complexity.

Various leak detection systems including both the hardware- and software- based methods are being employed by pipeline operators [16, 21] and also biological based detection method [17]. Of the hardware-based methods is the use of acoustics, fiber optics, ultra-Sonics, infrared radio-metrics, vapour or liquid sensing tubes, and cable sensors, while mass/volume balance, transient modeling, statistical/hypothetical analysis, and pressure analysis are examples of software-based methods [17]. By software-based detection methods, the leak is identified as a result of several detectable effects in terms of fluctuations in the monitoring pressures and/or flow rates [17]. Earlier studies shows that it is more difficult to detect by previous existing detection methods small leaks leading to spills of about 4-20 litres (1-5 gallons) compared to leaks with relatively large opening diameter [17].

By leak detection based on transient modeling, the leak is modeled as a pressure- and density-dependent function, which helps to improve the leak detection capability during transient flow such as pipeline shut down and starts up etc[17]. The inlet and outlet measurements of these flow parameters remain unchanged before the incident of a leak. But when there is a leak, the occurrence will send to both ends of the pipeline, signals which travel at the velocity of sound along the pipeline segments[17]. This effects a change in the measurement of pressure, flow rate and sometimes temperature given by the pressure sensors, flow-meters and temperature sensors respectively [17]. As a result of this, the variation in this thermodynamic flowing features help to recognize the advent of leak, locate it and determine its quantity [17].

And when there is a leak occurrence, the output and actual reading are different and the discrepancies in these can be used to identify the leak, locate it and estimate its rate [17]. Since this detection method accounts for the ample internal flow characteristics of the pipelines considering the segmental analysis, it is much applicable to the pipeline without considering the connection between the upstream and downstream [17].

In order to improve the efficiency and effectiveness of leak detection and localization in their pipeline network, most pipeline operators employ the use of two or more various types of leak detection and localization systems. It is worthy of note that in addition to computer based monitoring systems, other leak detection and localization methods which include aerial and land-based perambulation are employed.

Leak Detection Methods

Generally, there are two broad classes of leak detection systems – external and internal based systems. The internal based systems are electronic leak detection methods which include [12].

1) Balancing Systems (line balancing, volume balancing, mass balancing etc.)
2) Simple or combination "Rate of Change
3) Computational pipeline monitoring
4) Pressure/flow analysis or monitoring
5) Real time transient model leak detection system (RTTM-LDS) etc.
6) Statistical analysis LDS.

In this work, we are concern with the fundamentals and application of transient model-based leak detection and localization method.

Real Time Transient Modeling

Using the increasing computing power of modern digital computers, it is possible to calculate in real time the profiles for flow v, pressure p and density ρ (or temperature T) along the pipeline [12]. This is as known real time transient modeling (RTTM) system of leak detection and localization. It is expensive and complex but also most sensitive and most reliable. RTTM involves the computer simulation of pipeline conditions using advanced fluid mechanics and hydraulic modeling [8]. Calculations involving the momentum equation, the energy conservation equation and other numerous flow equations are typically used by the RTTM technique. RTTM software can predict the size and location of leaks by comparing the measured data for a segment of pipeline with the predicted modeled conditions[3]. The analysis According [3] is done in a three-step process. First, the pressure-flow profile of the pipeline is calculated based on measurements at the pipeline or segment inlet. Next, the pressure-flow profile is calculated based on measurements at the outlet. Third, the two profiles are overlapped and the location of the leak is identified as the point where these two profiles intersect. If the measured characteristics deviate from the computer prediction, the RTTM system sends an alarm to the pipeline controller [3]. The more instruments that are accurately transmitting data into the model, the higher the accuracy of and confidence in the model. Note that models rely on properly operating and calibrated instruments for optimum performance [3]. Calibration errors can result in false alarms or missed leaks, and the loss of a critical instrument could require system shutdown [3].

The advantage RTTM provides over other methods is its ability to model all of the dynamic fluid characteristics (flow, pressure, temperature) and take into account the extensive configuration of physical pipeline characteristics (length, diameter, thickness, etc.), as well as product characteristics (density, viscosity, etc.) [3, 5].

Layout of RTTM Based Leak Detection System [19]

Pipeline Observer

The heart of the leak monitoring system is the pipeline observer. It represents the flow-mechanics and thermodynamics along the length of the leak-free pipeline. For this purpose, pressure P_I and P_O are measured at inlet and outlet respectively. In addition, the temperatures of the fluid (batch) and density are required. The flow rates $\dot{M}_I$ and $\dot{M}_O$ are calculated from these values. These estimated values are compared with the measured values; the residuals $x \equiv M_I - \dot{M}_I$ and $y \equiv M_O - \dot{M}_O$ result. In a leak-free case, $x, y \approx 0$. If a leak occurs, deviations occur from which both the leak position X_{Leak} and the leak rate (speed, volume flow or mass flow) $\dot{M}_{Leak}$ can be derived.-

$$\dot{M}_{Leak} = x - y; \qquad (2.1)$$

$$X_{Leak} = \frac{-y}{x-y} L; \qquad (2.2)$$

(Where L is the length of the pipeline).

Leak Detection, How?

If there is no leak, the monitors estimates will be more or less in line with the data coming from the pipeline, in other words the remainder will be approximately 0. When a leak occurs, the remainder will change in a very characteristic manner, with the leakage rate being described as $\dot{V}_{Leak} = x - y$, with the leakage rate $\dot{V}_{Leak}$ in, for example m^3/hr.

Leak Detection Location (Locating the Leak), How?

Identification and isolation are important steps in minimizing the consequences of any leak. Leak detection systems are used in order to do both. In most cases, it is not possible to pinpoint the location of a leak from a remote location, but leak detection systems, utilized by properly trained and qualified controllers or dispatchers, can, in a vast majority of cases, determine an approximate location so that the affected segment can be isolated.

In figure 2.1 below, Measuring the straight line gradients (assuming that the friction factor f is known and the leak rate $\dot{M}_{leak}$ estimates are available) and calculation of the point of intersection therefore allow for leak location estimation [12]. If there is no leak, the transient pressure drop per unit length along the pipeline is constant; i. e. No leak, $\frac{dP}{dx} = f(\dot{M}_I) = constant$. If a leak now occurs, the flow rate upstream of the leak will be greater than the flow rate downstream of the leak; therefore the pressure drop per unit length upstream of the leak will also be greater than pressure downstream of the leak. i. e.

$$\frac{dP}{dx} f(\dot{M}_I) for\ 0 \leq x \leq x_{Leak} > \frac{dP}{dx} f(\dot{M}_O) for x_{Leak} < x \leq L \qquad (2.3)$$

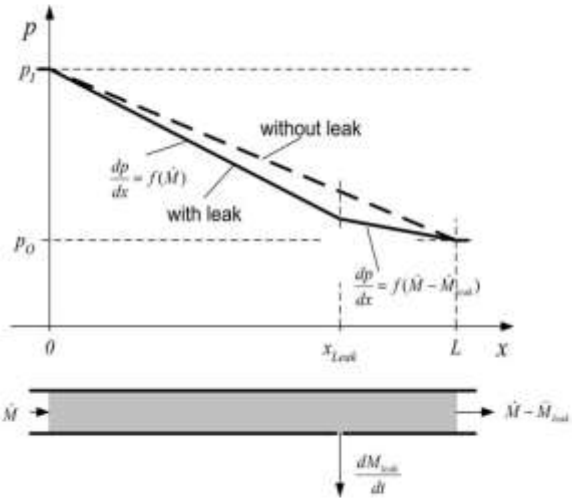

Fig-1: Leak Location with Gradient Intersection Method. Source [12, 19]

Leak Detection Reliability

Reliability is defined as a measure of the ability of the LDS to render accurate decisions about the possible existence of a leak on the pipeline[3, 6, 12], while operating within the domain instituted by the LDS design. According to [12], it follows that reliability is directly related to the probability;

- To detect a leak, given that a leak in fact exists, and
- To incorrectly declare a leak given that no leak has occurred.

A system is considered to be reliable if actual leaks are detected in consistency without false alarms.

Leak Detection Sensitivity

Leak detection sensitivity is a measure of the LDS capability to detect a leak of a certain size in a predetermined time without delay. Small leaks are not easy to detect; and the duration to set off an alarm or activatethe signals of some other components of the system are prolonged. Volume or mass balance systems are typically employed to detect smaller leaks that are not easily detectable. Larger leaks are more easily detected, but must be detected quickly.

Leak Detection Accuracy

LDS may provide additional leak information like leak location and leak rate. The validity of these leak parameter estimates constitutes another measure of performance referred to as accuracy.

Robustness

Robustness [7] is defined as a measure of the LDS ability to continue to operate and provide useful information, even under changing conditions of pipeline operation, or in condition where data is lost or suspect. An LDS is considered to be robust if it continues to function under such less than ideal conditions. Robust LDS typically are able to tolerate sensor failures using some kind of redundancy evaluation.

Preventing False Alarms

An important consideration when selecting a leakage monitoring system is the prevention of false alarms[19]. A number of measures have therefore been implemented to prevent these occurring[19].

Compensation for Line Packing

Compressibility of the fluid and elasticity of the pipe wall contributes to line packing[19].This means that overtime, more fluid flows into the pipeline than flows out of it; (assuming there is no leakage), particularly during transient operations [19]. This leads to major problems when using the "classical" quantitative comparison method, as this scenario tends to produce false alarms [19]. This rather restricts the use of quantitative comparison systems in practice, as they are often turned off when starting up or shutting down the pipeline [19]. This is a serious drawback of this type of system, as it is particularly during these times that hammer in the pipeline causes comparatively high risk of leakage [19]. The pipeline SCADA effectively compensate for line packing.

Compensation for Changes in Density and Temperature

Changes in temperature of the batch as a result of changes in temperature, e. g. caused by sudden changes in the weather, is another problem that often results in false alarm in conventional systems [19]. The SCADA also compensates for changes in density by including the temperature response in the pipeline monitor.

Basic Pipeline Modeling Equations for Leak Detection Systems

An integral part of a pipeline modeling system is the transient pipeline flow model [17]. By this model, the state of the pipeline is computed at every time step for which measured data are available [17]. This state of the pipeline is a vector set of pressures, temperatures and flow that helps in describing the fluids being transported at all points and segments within the pipeline system [17]. The solution to the derived model equations gives these quantities which define the behaviour of the system [17]. The basic fundamentals equations from which other thermodynamic equations on fluid mechanics are derived are the Continuity equation, the Momentum equation, the Energy equation [17].

The continuity equation also known as the mass balance equation is based on the law of conservation of mass. This entails that the difference in the mass flow in and out of a pipeline section or segment is equal to the rate of change of mass within the section[11, 18]. Mathematically, for a normal flow, the continuity equation can be expressed as [17];

$$\frac{\partial \rho A}{\partial t} + \frac{\partial \rho A v_x}{\partial x} + \frac{\partial \rho A v_y}{\partial y} + \frac{\partial \rho A v_z}{\partial z} = 0 \qquad (2.4)$$

But for a unidirectional (one-dimensional) flow in pipeline, Equation (2.63) becomes:

$$\frac{\partial \rho A}{\partial t}\Delta x + \frac{\partial \rho A v_x}{\partial x}\Delta x = 0 \qquad (2.5)$$

In the occurrence of a leak, the continuity equation becomes

$$:\frac{\partial \rho A}{\partial t}\Delta x + \frac{\partial \rho A v_x}{\partial x}\Delta x + M_l = 0 \qquad (2.6)$$

where the M_l is the leak rate of the equation (2.6).

The leak rate is more properly described by equation (2.1) as [19];

$$\dot{M}_{leak} = x - y$$

Where x is the characteristic discrepancy between measured and estimated flow rate at the inlet or upstream (i. e $x = M_I - \dot{M}_I$), while y is the characteristic discrepancy between the measured and estimated flow rate at the outlet or downstream (i. e. $y = M_O - \dot{M}_O$).

The leak position is also given by equation (2.2) as:

$$X_{leak} = \frac{-y}{x-y}L$$

The Momentum equation describes the force balance on the fluid within a segment of the pipeline. Its major requirement is that any imbalance or unbalanced forces result in acceleration of the fluid element. From Navier-Stokes equations, Cauchy Momentum Equations, the differential equation for the conservation of momentum in one-dimensional flow is [17][18]:

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x}\right) = -\frac{\partial p}{\partial x} + \mu\frac{\partial^2 v}{\partial x^2} + \rho g \qquad (2.7)$$

Substituting the viscosity μ from the expression for Reynolds' number considering and later substituting with the relation of frictional factor gives[17]:

$$\rho\frac{\partial v}{\partial t} + \left(\rho v\frac{\partial v}{\partial t}\right) + \frac{\partial p}{\partial x} + \left(\frac{\rho f v^2}{\partial x^2}\right) = 0 \qquad (2.8)$$

Substituting$p = P + \rho g H$ into eqn.(2.8) gives[17];

$$\rho\frac{\partial v}{\partial t} + \rho v\frac{\partial v}{\partial x} + \frac{\partial P}{\partial x} + \rho g\frac{\partial H}{\partial x} + \frac{\rho f v^2}{2D} = 0 \qquad (2.9)$$

Introducing the leak term into eqn. (2.9) gives [17];

$$\rho\frac{\partial v}{\partial t} + \left(\rho\frac{\partial v^2}{\partial x}\right) + \left(\frac{\partial P}{\partial x}\right) + \rho g\frac{\partial H}{\partial x} + \frac{\rho f v^2}{2D} + \rho v_l = 0 \qquad (2.10)$$

The energy equation states the rate of change of energy within a pipeline segment can be related equally to the difference in the energy flow into and out of the segment. Mathematically[9];

$$\rho\frac{\partial T}{\partial t}+\rho v\frac{\partial T}{\partial x}+\left(\frac{T}{c}.\frac{\partial P}{\partial T}.\frac{\partial v}{\partial x}\right)-\frac{\rho f v^3}{2cd}+\frac{4v}{cd}\left(T-T_g\right)=0 \quad (2.11)$$

These three equations (2.6, 2.10 and 2.11) is the set of one dimensional hyperbolic partial differential pipe flow equations used to govern the fluid characteristics within the pipeline where v is the one-dimensional velocity, ρ is the density of the fluid, P is the static pressure, H is the elevation, f is the frictional factor, v_l is the leak velocity, x is the spatial space and t is the time[17]. But since the leak considered in the transient model affects only the downstream temperature at the fluid flowing velocity, the equation of the energy conservation has an insignificant contribution to the leak detection[17]. Thus equation 2.11 is neglected and equations 2.6 and 2.8 describe the pipeline flow with a leak precisely and thus can be used to simulate accurately the impact of a leak on pipeline ends parameters [1, 2, 15, 17].

The pressure data are imputed into the observer and the flow rate values are estimated at normal flow (no leak) condition. Thus, when there is a leak, the estimated values will now be different from the measured values and the discrepancies of these mass flow rates at any time between the measured and the observed is

$$x,y=\begin{Bmatrix} x=M_I-\dot{M}_I \\ y=M_O-\dot{M}_O \end{Bmatrix} \quad (2.12)$$

At normal flow i.e. when there is no leak, the variations are zero. But when there is a leak, the location can be defined from equation 2.1 and 2.2.

The state pressures at any point i, and time j along the pipeline can be evaluated using the formula below [17, 20].

$$P_i^j=\sqrt{\left(P_0^j\right)^2+\left(\left(P_n^j\right)^2-\left(P_0^j\right)^2\frac{x_i^j}{L}\right)} \quad (2.13)$$

From equation 2.72, it can be observed that the system takes in the two measured pressures as major input and the model will estimate the upstream and downstream mass flow rates based on this.

This model uses the Goudar–Sonnad equation (a better and more accurate approximation of the Colebrook-white equation) to obtain the Darcy-Weisbach frictional factor and uses the Darcy-Weisbach equation to calculate the flow rate using the formula below [17]:

$$M_i^j=\sqrt{\frac{\pi^2\left(\rho_i^j\right)D^5(\Delta P)_i^j}{8f\left(x_i^j\right)}} \quad (2.14)$$

Where ρ_i^j is the density of the fluid at mesh point (i, j) and it is assume to be constant throughout the pipeline, $(\Delta P)_i^j$ is the pressure drop from the upstream end to the ith segment at j time index.

Review of Past Work

A number of pipeline leak detection models have been implemented on several pipeline systems [21]. However, many methods are hedged in with their shortcomings, which are, long response time, and incidence of false alarm reporting, etc. [1, 2]. The transient leakage detection is used to monitor whether pipeline is in a normal state by establishing the accurate pipeline model and utilizing perfect numerical methods. Comparatively speaking, the transient leakage detection method has the advantages of speediness and exactness. Gas pipeline leakage detection research based on transient simulation had begun since the early 1980s abroad. The transient leakage detection is a major application of transient simulation software, aiming to detect and locate pipeline rupture immediately [20].

In a study, [19] described the principles and application of transient model-based leak detection and localization system GALILEO for Krohne. A significant section was devoted to applications, in which the possibilities of general use in industry was examined and the results demonstrated that the system is suitable for use in industry. A whole range of experiments were carried out with different batches and operating conditions in the pipeline to obtain a reliable, general statement about the performance of the model. During evaluation, a distinction was made between three different pipeline operating conditions:

* Normal operation: The pipeline is operated largely in a steady state, normal is being pump.
* Normal operations with dynamics: The pipeline is dynamically excited by briefly closing a valve behind the pipeline outlet; as a result, pressure and flow waves, moving at the speed of sound, are superimposed on the nominal values.
* Start up: This is the most dynamic condition, which begins with starting the pumps and operating the valves and ends on reaching the nominal value.

The model presented has been proved in a practical application in which a leak along a 25km pipeline was detected in less than one minute after it has occurred and within less than three minutes the exact location where it occurred was spotted – to within only 100meters. The result demonstrates that the model is suitable for use in industry.

[12] proposed a model giving an overview of methodologies, methods and techniques for leak

detection and localization. He described the RTTM similar to that of [19] using the increasing computing power of modern digital computers to calculate in real time the profiles for flow velocity v, pressure p and density ρ (or temperature T) along the pipeline by applying the continuity, momentum and energy equations. The Shortcomings of [12] model are that the computation of heat flow per unit mass l_Q as well as the enthalpy involved requires an additional thermal model and special model extensions are required for multi-phase conditions and other non-standard conditions.

[13] proposed a set of two coupled one dimensional first order nonlinear hyperbolic partial differential equations governing the flow dynamics based the assumption that measurements are only taken available at the inlet and outlet of the pipe, and output is applied in the form of boundary conditions. The shortcoming of the model is that leak is only accurately quantified and located successfully when the pipeline is shut-down.

[20] have proposed a leakage detection model and the solution were based on the three conservation laws in hydromechanics and the state equation, which includes transient simulation model and volume balance model. Dynamic parameters involved in the model such as pressure, flow and temperature can be acquired through SCADA system. By analyzing the factors influencing leakage position, they came to a conclusion that leakage and outlet pressure are more important parameters compared to the coefficient of frictional resistance and pipeline diameter. The more leakage increases, the closer leakage point approaches pipeline outlet. Leakage location is closer to outlet when pipeline outlet pressure becomes bigger. But the model fails to account for line pack correction by assessing changes in volume due to temperature and/or pressure variations.

[4] described oil leak/spill processes from containment such as pipeline in order to adequately estimate oil spills and to justify an appropriate emergency action for minimizing spills. Internal diameters of pipes used in the study were within 4 inches. Leaks were simulated from plastic pipeline oil containment fitted with valves. The leak response with time when upstream and downstream valves were operated was studied. Within the internal diameters of pipelines considered in the tests, two ranges of leak characteristics were evident; "holding range" and "flowing range" characteristics. The consequences of these characteristics in the oil industry operations were discussed. Furthermore, in order to minimize spill in event of pipeline failure, it was observed that the optimum action on pipeline operational valves, was the immediate closure of upstream valve, followed by the downstream valve, nearly simultaneously. However the work has not been tested on large diameter pipelines that are carrying crude in real time, so no real time mathematical model for leak detection obtained yet. Future work will extend the test to larger diameter pipelines to attempt developing a mathematical approach for estimating limits of the "holding range" characteristics of pipelines given appropriate parameters and in-field test.

[17] presented a transient flow analysis of fluid in pipe line to account for imbalance in the continuity and momentum equations. Measurements of flow parameters at inlet and outlet of pipeline were used in developing the model. With this model, leakages in pipeline were easy to detect during start-up and shut-down. But the performance of the pipeline observer has a great effect on the efficiency of the model.

In this work, a model-based leak detection (and localization) system to detect and locate leak is intended to be achieved at a very low cost and to mitigate the quantity of oil spilled to the environment and to achieve the overall goal of safety. Measurement of pressure, temperature and flow data at both the inlet and outlet of the pipeline will be used in developing the equations derived from the imbalance in the continuity and law of conservation of momentum equations. The characteristics changes in the flow-mechanics and thermodynamics along a given length of pipeline will be used in detecting the leak, localize it and determine its flow rate. The dynamic parameters involved in this model such as pressure, flow and temperature will be acquired by SCADA (Supervisory Control and Data Acquisition) system, while the friction factor will be considered in estimating the parameters at the inlet and outlet of the pipeline section. The pressure drop per unit length, the leak flow rate and the leak position will be calculated from the remainders (i.e. the discrepancies between the measured and the estimated values at the inlet and outlet of the given pipeline).

METHODOLOGY

In this work, transient model-based leak detection and localization technique for crude oil pipelines was achieved by:

1. Giving a description of the model method for the leak detection, localization and quantification.

Standard data of pipeline (commercial steel) configuration and the (Nigerian Bonny Light) Crude Oil were obtained from literature, while dynamic data were obtained from the library of and the SCADA system at the control room of the Nigeria Petroleum Development Company (NPDC), Olomoro field.

2. Simulating the model with the data obtained from both literature and the crude oil exploration field.

Description of the Model Method for the Leak Detection and Localization.

The purpose of this section is to obtain a suitable model for leak detection and its location. The procedure to achieve this is as follows:

a. Calculate the pressure drop at the inlet and outlet and compare with the domain established pressure drop, in our case, it should not be greater than 1Kpa.
b. Calculate the profile velocity.
c. Calculate the Renold's number for the flow.
d. Calculate the Darcy frictional factor for the flow.
e. Calculate the state pressure at the inlet and the pressure drop at the inlet.
f. Calculate the mass flow rate at the inlet and outlet.
g. Calculate the discrepancies (x and y) in flow rates at the inlet and outlet of the pipe.
i. Calculate the leak flow rate, $\dot{M}_{leak}$
j. Calculate the leak position, X_{leak}

a. Calculate the Pressure Drop

The pressure drop or change in pressure is the discrepancies between the inlet pressure and the outlet pressure. It is obtained using:

$$\Delta P = P_I - P_O \qquad (3.1)$$

Where ΔP= Pressure drop, P_I= Inlet pressure and P_O= Outlet pressure

b. Calculate the Velocity Profile

The velocity profile is the average velocity of the fluid which is being used since the velocity along the
pipeline is not uniform. It is obtained using:

$$v = \frac{D^2}{32\mu} \cdot \frac{\Delta P}{L} \qquad (3.2)$$

Where v= average velocity, D = diameter of pipe, μ = viscosity, ΔP = Pressure drop &L = length of pipe.

c. Calculate the Renold's Number, *Re*

The Renold's number for the flow is calculated using the relation: $Re = \frac{\rho D v}{\mu}$ (3.3)

Where ρ = density of fluid, D = diameter of pipe, v = average velocity, μ = viscosity

d. Calculate the Darcy Frictional Factor

One of the causes of pressure drop in a pipeline is friction. The Darcy friction takes care of the pressure loss. The Goudar-Sonnad equation is a better and more accurate approximation of the Colebrook-white equation hence it is adapted by this model to obtain the Darcy-Weisbach frictional factor. It is obtained using the relations:

$$a = \frac{2}{\ln(10)};\ b = \frac{\varepsilon/D}{3.7};d = \frac{\ln(10)Re}{5.02};\quad S = bd + \ln(d)\quad ;$$
$$q = s^{s/(s+1)};g = bd + \ln\frac{d}{q};z = \ln\frac{q}{g};D_{LA} = z\frac{g}{g+1};$$
$$D_{CFA} = D_{LA}\left(1 + \frac{z/2}{(g+1)^2 + (z/3)(2g-1)}\right);$$
$$\frac{1}{\sqrt{f}} = a\left[\ln\left(\frac{d}{q}\right) + D_{CFA}\right] \qquad (3.4)$$

Where ε = roughness of pipe wall, D = diameter of pipe, ε/D = relative roughness, Re = Renold's number, f = Darcy frictional factor

e. Calculate the Inlet State Pressure and its Pressure Drop

The state pressure at a point$x$, 1m at the inlet of the pipeline is evaluated using the formula below:

$$P_x = \sqrt{P_0^2 + (P_I^2 - P_0^2)\frac{x}{L}} \qquad (3.5)$$

Where P_x = State pressure at point x, P_0 = Outlet pressure, P_I = Inlet pressure, x = a point (1m) at the inlet, L = Length of pipe.

Then the pressure drop at a point (1m) within the inlet is calculated with the relation of equation (3.1)

$$\Delta P_x = P_0 - P_x$$

f. Calculate the Inlet and Outlet Mass Flow Rates

The model uses the Darcy-Weisbach equation to determine the mass flow rate at a point 1m along the inlet and at the outlet as follow:

$$M_I = \sqrt{\frac{\pi^2 D^5 \rho \Delta P_x}{8fx}} \qquad (3.6a)$$

Where M_I = Inlet mass flow rate, D = diameter of pipe, ρ = density of fluid, ΔP_x = Pressure drop at a point x (1m) from inlet, f = Darcy-Weisbach Frictional factor, x = a point (1m) at the inlet.

$$M_o = \sqrt{\frac{\pi^2 D^5 \rho \Delta P}{8fL}} \qquad (3.6b)$$

Where M_o = Outlet mass flow rate, D = diameter of pipe, ρ = density of fluid, ΔP = Pressure drop along the pipeline, f = Darcy-Weisbach Frictional factor, L = Length of pipeline.

g. Calculate the Discrepancies

Before the advent of a leak, the measured (inlet and outlet) flow rates and the observed/estimated (inlet and outlet) flow rates are relatively equal that their remainders are zeros or approximately equal to zero.

$$x = M_I - \dot{M}_I \qquad (3.7a)$$

Where x = discrepancies of mass flow rates at the inlet, M_I = observed/estimated inlet mass flow rate and $\dot{M}_I$ = Measured inlet mass flow rate.

$$y = M_O - \dot{M}_O \qquad (3.7b)$$

Where y = discrepancies of mass flow rates at the outlet, M_O = observed/estimated outlet mass flow rate and $\dot{M}_o$ = Measured outlet mass flow rate.

h. Calculate the Leak Flow Rate

The difference between the discrepancies of mass flow rates at the inlet and outlet of the pipeline is the mass flow rate of the leakage. It is given as:

$$\dot{M}_{Leak} = x - y \quad (3.8)$$

i. Calculate the Leak Position

The leak position is a function of the leak flow rate and the length (L) of the pipeline. It is given as:

$$X_{Leak} = \frac{-y}{x-y} L \quad (3.9)$$

Method of Data Collection

The parameters needed for the simulation of the model are the fluid density, inlet and outlet flow rates (of normal condition of no-leak), pressures and temperatures, length, diameter and roughness. These parameters were obtained from pipeline (commercial steel) configuration, the transporting fluid (Nigerian Bonny Light Crude Oil) properties and the SCADA system at the control room and the archive of the Nigeria Petroleum Development Company Limited (NPDC), Olomoro field base on a horizontal pipeline carrying crude oil from the Olomoro field to the Ughelli pumping station (UPS) truck line.

With the available data collected (table 1 & 2 below), this model is simulated with graphical plots using excel software.

Table 1: Standard Parameters of Pipeline (Commercial Steel) Configuration and the Nigerian Bonny Light Crude Oil Properties

Parameters	Values	Units
Density of Fluid, ρ	834.2	Kg/m³
Dynamic Viscosity, μ	0.00172	Pa.s
Diameter of pipe, D	0.3556	Metre
Length of pipe, L	2000	Metre
Roughness of pipe, ε	0.0000457	Metre

Source: (17); NPDC archive, Olomoro field (n.d)

Table 2: SCADA System Dynamic Parameters

Parameters	Value	Unit
Mass flow rate (input), $\dot{M}_I$	72.08	Kg/s
Mass flow rate(output), $\dot{M}_0$	72.05	Kg/s
Pressure (input) P_I	120	KPa
Pressure (output) P_0	104	KPa
Temperature (input), T_I	22.5	°C
Temperature (output), T_0	20.5	°C

Source: NPDC Daily SCADA Data Report Sheet, Olomoro field, 2015

DATA ANALYSIS AND RESULTS DISCUSSION

It is a known fact that there is usually pressure drop along crude oil carrying pipelines. This is as a result of height elevation, kinetic changes and friction along the pipelines. This change in pressure is usually known (by calculation and enveloped or customized in the system) and remains constant through the operations, except there is an external influence or abnormal conditions.

During normal condition of operations at the Olomoro field of the Nigerian Petroleum Development Company, it is observed that the inlet pressure is usually greater than the outlet pressure. The inlet pressure is usually 120KPa, while outlet pressure varies within the range of 119 – 119.5KPa. That is the pressure drop is within the range of 0.5 – 1.0KPa. If the already known pressure drop increases more than that range when there is no change in the height elevation, kinetics or friction, an abnormal condition has set-in and a leak is suspected.

From the SCADA data, the wide range between the inlet pressure and outlet pressure is vivid. Therefore substituting the values $P_I = 120KPa$ and $P_2 = 104KPa$ (Table 3.2) in equation (3.1), the pressure drop is:

$$\Delta P = P_I - P_O = 120 - 104 = 16Kpa$$

It is therefore expedient for the mass flow rate at the inlet and outlet of the pipeline to be estimated. To achieve this, the average velocity V, Renold's numberRe, frictional factor$f$ and changes in pressure at the inletΔP_x and outletΔP_L are needed. Substituting the values $D = 0.3556m$, $\mu = 0.00172kgms^{-2}$., $\Delta P = 16KPa$,$L = 2000m$ (Table 3.1) in equation (2);

$$V = \frac{D^2}{32\mu} \cdot \frac{\Delta P}{L} = \frac{0.3556^2}{32\mu} \cdot \frac{16(1000)}{2000} = 18.38m/s$$

Substituting the values $\rho = 834.2kg/m^3$, $D = 0.3556m$, $\mu = 0.00172kgms^{-2}$. (Table 3.1) and $V = 18.38m/s$ in equation (3);

$$Re = \frac{\rho DV}{\mu} = \frac{834.2 \times 0.3556 \times 18.38}{0.00172} = 3169925.08$$

The Goudar-Sonnad equation which is a better and more accurate approximation of the Colebrook-white equation is used to obtain the Darcy-Weisbach frictional factor as follows in equation (3.4):

$$a = \frac{2}{\ln(10)} = 0.8686$$

$$b = \frac{\varepsilon/D}{3.7} = \frac{0.0000457/0.3556}{3.7} = 0.0000347$$

$$d = \frac{\ln(10) . Re}{5.02} = \frac{In(10) \times 3169925.08}{5.02}$$

$$= 1453988.49 s = bd + \ln(d)$$

$$= 0.0000347 \times 1453988.49$$

$$+ \ln(1453988.49) = 64.64$$

$$q = s^{s/(s+1)} = 64.64^{64.64/(64.64+1)} = 60.66 g$$

$$= bd + ln\frac{d}{q}$$

$$= 0.0000347 \times 1453988.49$$

$$+ ln\frac{1453988.49}{60.66} = 60.54$$

$$z = ln\frac{q}{g} = ln\frac{60.66}{60.54} = 0.00198$$

$$D_{LA} = z . \frac{g}{g+1} = 0.00198 \times \frac{60.54}{60.54+1} = 0.00195$$

$$D_{CFA} = D_{LA}\left(1 + \frac{\frac{z}{2}}{(g+1)^2 + \left(\frac{z}{3}\right)(2g-1)}\right)$$

$$= 0.00195\left(1 + \frac{0.00198/2}{(60.54+1)^2 + (0.00198/3)(2 \times 60.54 - 1)}\right)$$

$$= 0.00195$$

$$\frac{1}{\sqrt{f}} = a\left[ln\frac{d}{q} + D_{CFA}\right] = 0.8686\left[ln\frac{1453988.49}{60.66} + 0.00195\right] \qquad f = 0.013$$

To calculate the pressure drop at the inlet, the state pressure at the inlet is needed. At a point $x = 1m$upstream(inlet) of the pipeline, the state pressure is obtained by substituting $P_I = 120KPa$, $P_O = 104KPa$, $L = 2000m$ in eqn. (3.5):

$$P_x = \sqrt{P_I^2 + (P_O^2 - P_I^2)\frac{x}{L}}$$

$$= \sqrt{120^2 + (104^2 - 120^2)\frac{1}{2000}}$$

$$= 119.9851KPa$$

And the change in pressure at the inlet is obtained by substituting the above in eqn. (3.1):

$$\Delta P_x = P_I - P_x = 120 - 119.9851 = 0.015Kpa$$

Therefore, the mass flow rate at the inlet of the pipeline is obtained by substituting above parameters in equation (3.6):

$$M_I = \sqrt{\frac{\pi^2 D^5 \rho \Delta P_x}{8fx}}$$

$$= \sqrt{\frac{\pi^2 \times 0.3556^5 \times 834.2 \times 0.015 \times 1000}{8 \times 0.013 \times 1}}$$

$$= 82.17kg/s$$

Similarly, at the downstream (outlet) of the pipeline;

Change in pressure$= \Delta P_L = P_I - P_O = 120 - 104 = 16Kpa$. Therefore, the mass flow rate at the outlet is obtained using (3.6b):

$$M_O = \sqrt{\frac{\pi^2 D^5 \rho \Delta P}{8fL}}$$

$$= \sqrt{\frac{\pi^2 \times 0.3556^5 \times 834.2 \times 16 \times 1000}{8 \times 0.013 \times 2000}} = 60.01kg/s$$

Comparing the estimated mass flow rates with the measured mass flow rates at the inlet and the outlet of the pipeline (equation 3.7a & b) the discrepancies are vivid. From these discrepancies, the leak flow rate is determined (Using equation 8).

Discrepancies;

$x = M_I - \dot{M}_I = 82.17 - 72.08 = 10.09$kg/s

$y = M_O - \dot{M}_O = 60.01 - 72.05 = -12.04$kg/s

Therefore, the leak flow rate is

$$\dot{M}_{Leak} = x - y = 10.09 - (-12.04) = 22.13kg/s$$

And the leak location is obtained from equation (9) as

$$X_{Leak} = \frac{-y}{x-y}L = \frac{-(-12.04)}{22.13} \times 2000 = 1088.12m$$

The table below summarizes the steps and results of the leak detection and localization model.

Table 3: Summary of the Result of the Leak Detection and localization model Data Analysis

Quantity	***Value***
Pressure Drop, ΔP	$16KPa$
Average Velocity, V	$18.38m/s$
Renold's Number Re	3169925.08
Darcy-Weibach frictional factor, f	0.013
State pressure at a point upstream of the inlet, P_x	$119.9851KPa$
Pressure Drop at the inlet, ΔP_x	$0.015KPa$
Mass Flow Rate at Inlet, M_I	$82.17kg/s$
Pressure Drop at Outlet, ΔP_L	$16KPa$
Mass Flow Rate at Outlet, M_O	$60.01kg/s$
Discrepancy at Inlet, x	10.09kg/s
Discrepancy at Outlet, y	−12.04kg/s
Leak Flow Rate, $\dot{M}_{Leak}$	$22.13kg/s$
Leak Location, X_{Leak}	$1088.12m$

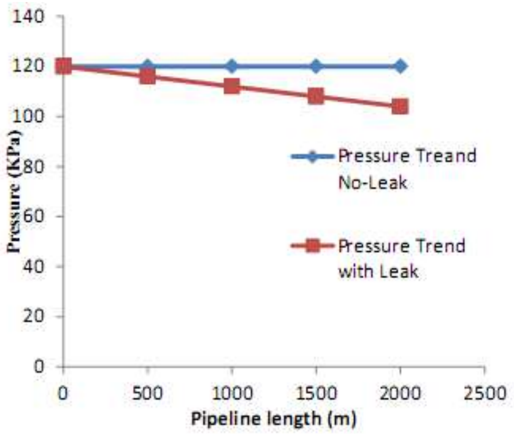

Fig-2: Plot for Pressure Trend at Inlet and Outlet of the Pipeline for Leak incident and No-leak incident

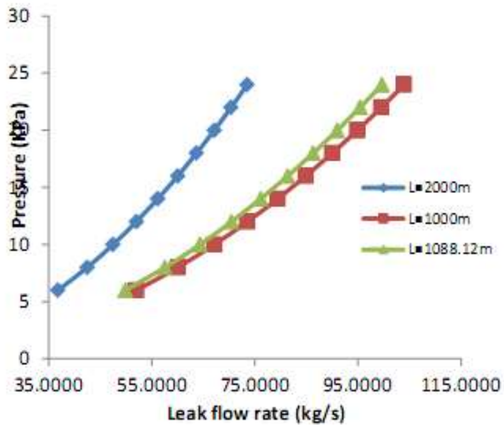

Fig-3: A plot of the change of pressure and the leak flow rate

From the data analysis above, it is seen that Leakages in pipelines are easy to detect during operations by merely observing the pressure along the pipelines. A drastic or an unusually drop in pressure (when order factors that cause change in pressure are constant) signals a leak and will often than not validates it. Figure 2 above shows a plot for the upstream and downstream pressure trends for leak and no-leak incidents. It is clear that there is pressure change along the pipeline from the inlet down to the outlet when there is no leak. This is normal because the turbulent flow of the crude oil along the pipeline causes friction and kinetic changes as the crude oil travels through the pipe. However this change in pressure (which is enveloped or customized in the system) is almost unnoticed as depicted by the "No-leak pressure trend" in the diagram above. This pressure drop varies between 120 and 119KPa, that is to say that the maximum pressure change cannot exceed 1KPa in normal condition where there is no leak. On the other hand, the drastic change in pressure is vivid. The pressure drops from 120KPa down to about 105KPa. This change is clear enough to suspect a leak as the pressure drop is about 15KPa. Figure 3 shows a plot of pressure changes versus leak flow rate at different lengths, it indicates that changes in pressure is directly proportional to the square of leak flow rates and the square of leak flow rate is inversely proportional to the length of the pipe. Based on this model, a leak incident in a horizontal pipeline carrying Nigeria bonny light crude oil from the Nigeria Petroleum Development Company Limited, Olomoro flow-station into UPS (Ughelli Pump Station) truck line was detected. The analysis disclosed the leak position to be 1088.12m from the inlet of the pipeline. However the actual leak position discovered after excavation of the leak pipeline was 1100m from the inlet a difference of 11.88m from the actual leak position. From the analysis, we saw that pressure drop along the pipeline length has a great influence on the leak. The leak characterizations were assessed using the discrepancies procured from flow rates (both measured and estimated) and subsequently the leak position as evaluated using the pressure drop at the ends of the pipeline.

CONCLUSIONS & RECOMMENDATIONS

The aim of this work has been to develop a transient model-based leak detection and localization technique base on the present state of technology in Nigeria; this has been achieved by mere observations from pressure drop and has been proved in practical application. Although the transient model has merit of swiftness and comfort, the accuracy of the leakage location is still an issue.

A range of likely occurrence of the leak what is usually obtained and not the exact position. Based on our model, the following conclusions have been drawn:

• Transient modeling for pipeline made it quick and easy for leak to be detected.

• Leakages in pipeline are easy to detect during normal operations.

• Transient modeling with SCADA on the background less expensive.

• The SCADA (***S****upervisory* ***C****ontrol* ***A****nd* ***D****ata* ***A****cquisition*) system employed make it easier for even more complex pipeline leaks to be detected and much data to be monitored online.

Based on this work, the recommendation made are as follows:

***** More work is still needed to be done to improve on leak exact position.

* All dynamic measuring instruments must be accurately calibrated.

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