Modeling and Simulation of a Leak Detection for Oil and Gas Pipelines via Transient Model: A Case Study of the Niger Delta

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Abstract
This research project introduces the transient flow analysis of fluid within the pipeline to account for the imbalance in the continuity equation and law of conservation of momentum. The transient model is suitable for compressible flow and a variety of pipeline configuration. Measurement of the pressure, flow and temperature data at both the upstream and downstream ends of the pipeline are used in developing the equations to govern the system in detecting the leak, localize it and determine its flowrate. This model was developed using MATLAB programming. A simulated leak in a horizontal oil pipeline is considered here to demonstrate this leak detection method. By this model, for a leak incident in a horizontal pipeline of 2000m and diameter 0.3556m transporting Nigeria bonny light crude oil, the leak is located at 1433.5m from the upstream end which is 18.5m away from the actual leak location.
Keywords: transient, pipeline, leak detection, upstream, downstream, MATLAB

1. Introduction

Hydrocarbons, very important sources of energy are been produced from oil or gas reservoirs. Even in intermediate processing of these hydrocarbons until they are present in useable form, there is requirement for at least one or two unit operations. The operations will require connections with one another through the aids of pipelines. 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.

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. Due to the vast mileage of pipelines throughout the nation, it is important that dependable leak detection systems are used to promptly identify when a leak has occurred so that appropriate response actions are initiated quickly. The swiftness of these actions can help reduce the consequences of accidents or incidents to the public, environment, and facilities. Leak detection systems capable of locating the position of the leak are obviously of an environmental kind. But the economical aspect of it is also important. 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.

Various leak detection systems including both the hardware- and software- based methods are being employed by pipeline operators (Zhang, 1997; Wang et al., 2001; Theakston and Larnaes 2002; Liu et al. 2005; Batzias et al., 2011) and also biological based detection method. Of the hardware-based methods is the use of acoustics, fiber optics, ultrasonics, infrared radiometrics, 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. 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 (Mastandrea et al. 1990; Bonn 1998). 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 (Mastandrea et al. 1990; Cranswick 2001; Teal 2003).

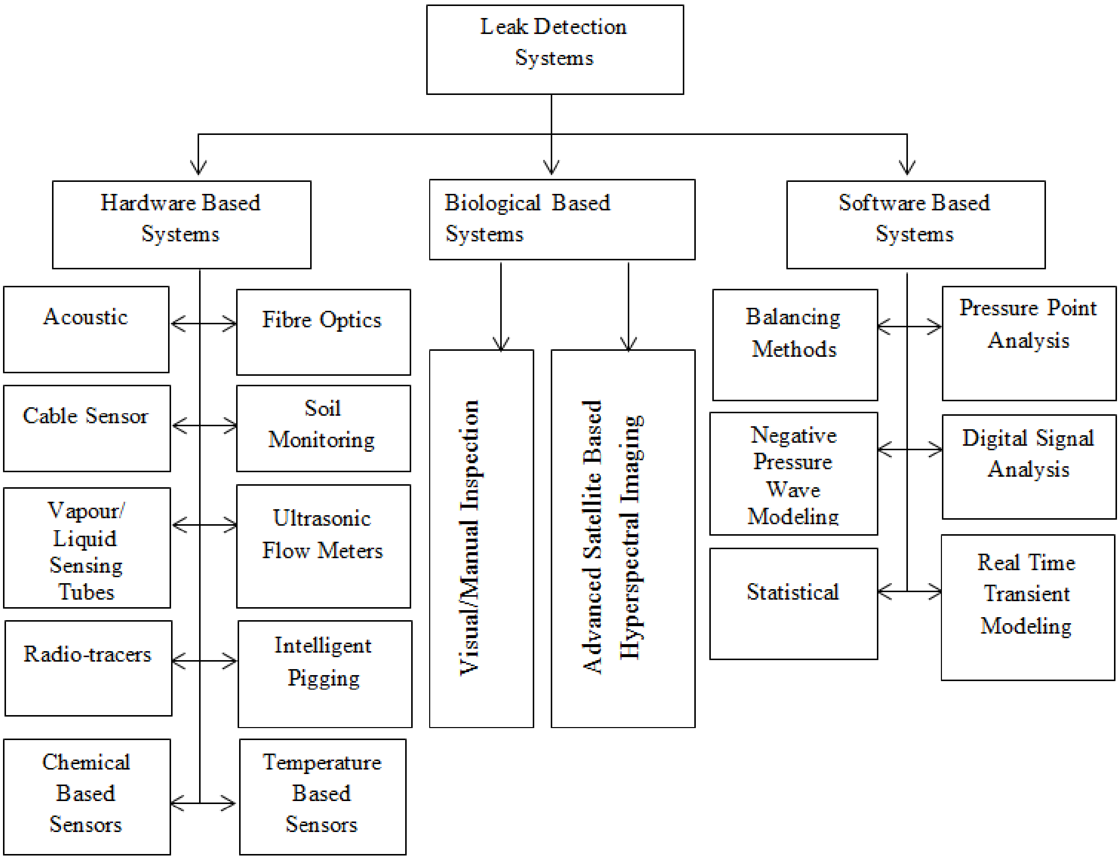

Figure 1:Classification of Oil/Gas Leak Detection Systems based on their Technical Nature

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 start up etc. The upstream and downstream measurements of these flow parameters remain unchanged before the incident of a leak. 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. This effect to change in the measurement of pressure, flow rate and sometimes temperature given by the pressure sensors, flowmeters and temperature sensors respectively. 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.

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. 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.

2. Basic Pipeline Modeling Equations

An integral part of a pipeline modeling system is the transient pipeline flow model. By this model, the state of the pipeline is computed at every time step for which measured data are available. 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. The solution to the derived model equations gives these quantities which define the behaviour of the system. The basic fundamentals equations from which other thermodynamic equations on fluid mechanics are derived are the Continuity equation, the Momentum equation, the Energy equation.

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. (Bird R.B. et al, Frank 2003, Robert H. et al 1999) Mathematically, for a normal flow, the continuity equation can be expressed as

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho A v_x)}{\partial x} + \frac{\partial(\rho A v_y)}{\partial y} + \frac{\partial(\rho A v_z)}{\partial z} = 0 \quad (1)$$

But for a unidirectional (one-dimensional) flow in pipeline, Equation 1 can becomes

$$\frac{\partial(\rho A)}{\partial t}\Delta x + \frac{\partial(\rho A v_x)}{\partial x}\Delta x = 0 \qquad (2)$$

In the occurrence of a leak, the continuity equation becomes

$$\frac{\partial(\rho A)}{\partial t}\Delta x + \frac{\partial(\rho A v)}{\partial x}\Delta x + M_l = 0 \qquad (3)$$

where the M_l is the leak rate of the equation (3). Dividing equation 3 throughout by Δx and letting Δx approach zero gives

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial(\rho A v)}{\partial x} + M_l \cdot \delta(x - x_l) = 0 \qquad (4)$$

The Dirac function is defined as (Wang et al 200 $\delta(x - x_l) = \frac{du(x-x_l)}{dx} = \begin{cases} 0, & x \neq x_l \\ \infty, & x = x_l \end{cases}$

And $\lim_{\varepsilon \to 0} \int_{x_l-\varepsilon}^{x_l+\varepsilon} \delta(x - x_l)dx = 1$ (5)

where ε is a small distance on the either side of the leak. Note that $\delta(x - x_l)$ has dimension of $length^{-1}$.

and $u(x - x_l) = \begin{cases} 0, & x < x_l \\ 1, & x \geq x_l \end{cases}$ (6)

Where u is the Heaviside unit step function.

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 (Robert H. et al 1999)

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 v}{\partial x^2}\right) + \rho g \qquad (7)$$

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

$$\rho\frac{\partial v}{\partial t} + \left(\rho v\frac{\partial v}{\partial x}\right) + \left(\frac{\partial p}{\partial x}\right) + \left(\frac{\rho f v^2}{2D}\right) = 0 \qquad (8)$$

Substituting $p = P + \rho g H$ into equation (8) gives

$$\rho\frac{\partial v}{\partial t} + \left(\rho v\frac{\partial v}{\partial x}\right) + \left(\frac{\partial P}{\partial x}\right) + \rho g\frac{\partial H}{\partial x} + \left(\frac{\rho f v^2}{2D}\right) = 0 \quad (9)$$

Introducing the leak term into equation 9 gives

$$\rho\frac{\partial v}{\partial t} + \left(\rho\frac{\partial v^2}{\partial x}\right) + \left(\frac{\partial P}{\partial x}\right) + \rho g\frac{\partial H}{\partial x} + \left(\frac{\rho f v^2}{2D}\right) + \rho V_l = 0 \qquad (10)$$

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, (Chis T. 2007)

$$\rho\frac{\partial T}{\partial t} + \rho v\frac{\partial T}{\partial x} + \left(\frac{T}{c}\cdot\frac{\partial P}{\partial T}\cdot\frac{\partial v}{\partial x}\right) - \frac{\rho f v^3}{2cd} + \frac{4U}{cd}(T - T_g) = 0 \qquad (11)$$

These three equations (4, 10 and 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. 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. Thus equation 11 is neglected and equations 4 and 10 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 (Dinis et al. 1999; Emara et al. 2002; Abhulimen and Susu 2004; Bratland 2009; Kam 2010). But based on present mathematical concept, the leak rate as well as its location cannot be obtained from those two equations (Equations 4 and 10), thus a better method is employed.

In this work, the following assumptions were made: (i) pipe cross-sectional area remains constant; (ii) isothermal and adiabatic flow; (iii) unidirectional (one-dimensional flow); (iv) no chemical reaction between the transporting fluid and internal wall of the pipe; (v) constant density throughout the pipeline segments; (vi) homogeneous fluid (i.e. either oil or gas) being transported in the pipeline.

3. The Leak Event: Its Diagnosis and Localization

For a normal flow in the pipeline, the pressure and mass flow rate profiles will be like the solid blue and red lines in the figure 2 below.

When there is a wholly developed leak in the system, the profiles will be like the dashed blue and red lines as shown in figure 3.

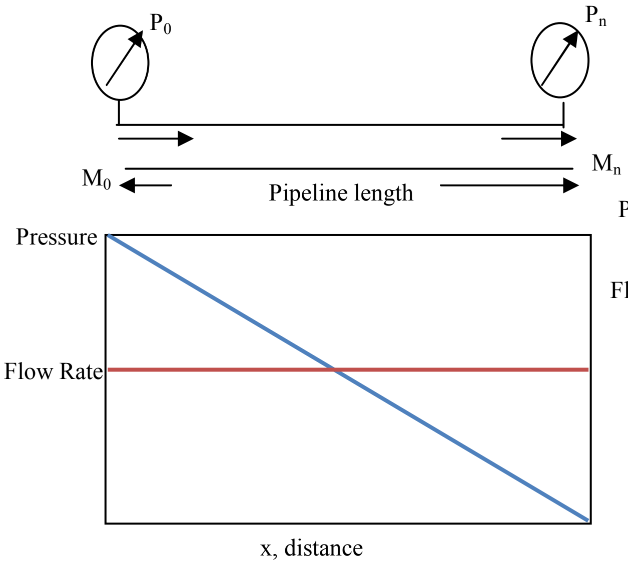

Figure 2: Pipeline Normal Flow Profiles

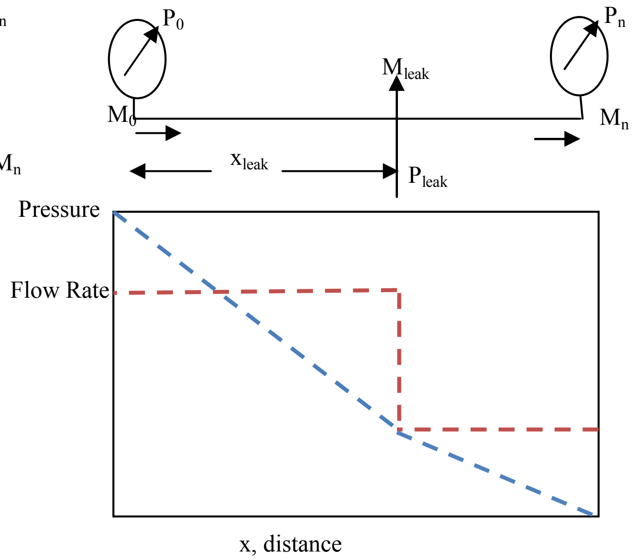

Figure 3: Pipeline Leak Profiles

The pressure data for the upstream and downstream are fed as inputs into the model and the model will consider the pressure profiles as the dashed blue (without leak) and estimate a flow rate (the dashed red lines). Thus the estimated flow rate will be different from the measured flow rate at the pipeline ends. Thus the mass flow rate variations between the estimated and measured at both the upstream and downstream end of the pipelines is a function of the leak rate and location which will help in the diagnosis, location and quantification of a leak.

It can be observed that 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 ***j*** between the measured and the observed is

$$e^j = \{e_i(j),\ i = 1,2\} = \left\{\begin{matrix} e_1(j) \\ e_2(j) \end{matrix}\right. = \left\{\begin{matrix} M_0^j - \bar{M}_0^j \\ M_n^j - \bar{M}_n^j \end{matrix}\right. \qquad (12)$$

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 4 as a uniform density function since the interval of the pipeline segment is known as $\Delta\mathbf{x}$ and constant and the leak position is constant. Thus, it can be given as

$$f(x) = \frac{1}{L} \qquad (13)$$

For accurate results by the observer, the discrepancies will only appear and change with the occurrence of a leak, its location and rate. The discrepancies can be calculated as the area bounded by the mass flow rate and the leak location function as follows:

$$e_1(t) = \int_{-\infty}^{t} \int_{0}^{x_l} f(x) \cdot M_l(s) \cdot ds \cdot dx \qquad (14)$$

$$e_2(t) = \int_{-\infty}^{t} \int_{x_l}^{L} f(x) \cdot M_l(s) \cdot ds \cdot dx \qquad (15)$$

Since *f(x)* has been defined as a uniform density function from equation 13, the integration can be considered as the mean value of the random variable *x* over the time period, there is a need for the introduction of the mathematical expectations *Es* of the discrepancies. Thus, equations 14 and 15 can be expressed as

$$E(e_1(t)) = \frac{x}{L} E(M_l(t)) \qquad (16)$$

$$E(e_2(t)) = \frac{x-L}{L} E(M_l(t)) \qquad (17)$$

Comparing both equations 16 and 17 since the leak is identical, the leak can be located using by discrete processing using the equation below:

$$x_l^j = \frac{L}{1 - \frac{E(e_2^j)}{E(e_1^j)}} \qquad (18)$$

For each index of time, the leak location will be calculated and updated. This changes randomly if there is no leak but when there is an occurrence of a leak, they converge and approach the actual value rapidly and keep it

constant while the leak still exist.
The occurrence of a leak can be diagnosed by the boundary conditions as stated in equation 19 and its rate can be calculated using equation 20.

$$\frac{E(e_2^j)}{E(e_1^j)} = \begin{cases} < 0, & leak \\ \geq 0, & \text{no leak, normal flow} \end{cases} \qquad (19)$$

$$M_l^j = E(e_1^j) - E(e_2^j) \qquad (20)$$

where E is the mathematical expectation of the discrepancies over a period of time.

4. Methodology

Based on the above analysis, a better method to characterizing the leak is by considering a robust transient flow model other than those in equations 4 and 10. This is achieved by considering the pipeline as a system of grids or segments with the flow features as a function of the spatial space x and time t.
With the length of the pipeline to be L, choosing integer n and defining the step size as Δx in the space axis for which

$$\Delta x = \frac{L}{n} \qquad (21)$$

The pipeline grid lines which are lines defined by $x = x_i$ and $t = t_j$ and their intersections (i.e. the mesh points of the grids) can be represented as shown in figure 4 below.

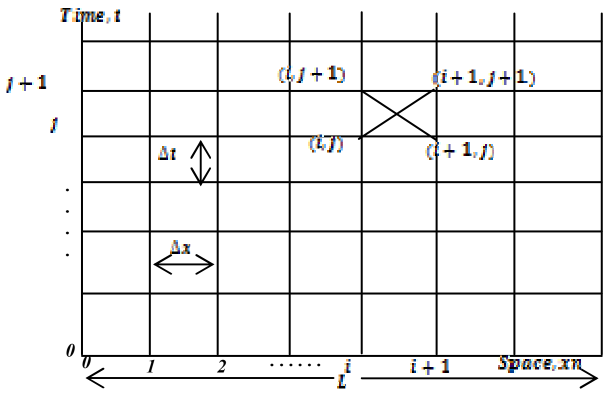

Figure. 4 The Pipeline Grid

Applying difference quotient to the central point of each grid, the flow can be modeled with the equation 22:

$$\begin{cases} \text{State Variables} \\ X = \{M_0, P_0, M_1, P_1, M_2, P_2, \ldots, M_{n-1}, P_{n-1}, M_n, P_n\}^t \\ \text{State Equation:} \\ X^{j+1} = F(X^j, U^{j+1}) \\ \text{System Input:} \\ U^{j+1} = \{P_0^{j+1}, P_n^{j+1}\}^t \\ \text{System Output:} \\ Y^{j+1} = \{M_0^{j+1}, M_n^{j+1}\}^t \end{cases} \qquad (22)$$

Where subscript is the grid index from 0 to n and the superscript j is the time index. For every mesh point (i, j), the state pressures of the pipeline can be evaluated using the formula below (Yang et al 2011).

$$P_i^j = \sqrt{(P_o^j)^2 + \left(((P_n^j)^2 - (P_o^j)^2)\frac{x_i^j}{L}\right)} \qquad (23)$$

From equation 22, 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 the previous system time state.

The model uses the Darcy-Weisbach equation to calculate the flow rate using the formula below (Wang

S. and Carroll J.J. 2006)

$$M_i^j = \sqrt{\frac{\pi^2(\rho_i^j)D^5(\Delta P)_i^j}{8f(x_i^j)}} \quad (24)$$

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.

The parameters needed for the simulation are obtained from the pipeline (commercial steel) configuration and the transporting fluid (Nigerian Bonny Light Crude Oil) properties and are presented in the table 1 below. The procedural detail is summarized in the flowchart shown below in figure 5. The modeling and simulation was developed using the graphical plot in MATLAB.

TABLE 1: Parameters for A Straight, Horizontal Pipeline Carrying Oil

Parameter	Value	Unit
ρ	834.2	kg/m^3
μ	0.00172	Pa.s
n	200	–
L	2000	Metre
D	0.3556	Metre
$Roughness, \varepsilon$	0.0000457	Metre
$M_{(0,0)}$	71.48	kg/s
$P_{(0,0)}$	120	KPa
$T_{(0,0)}$	295.2	Kelvin
$M_{(L,0)}$	71.45	kg/s
$P_{(L,0)}$	98	KPa
$T_{(L,0)}$	293.45	Kelvin

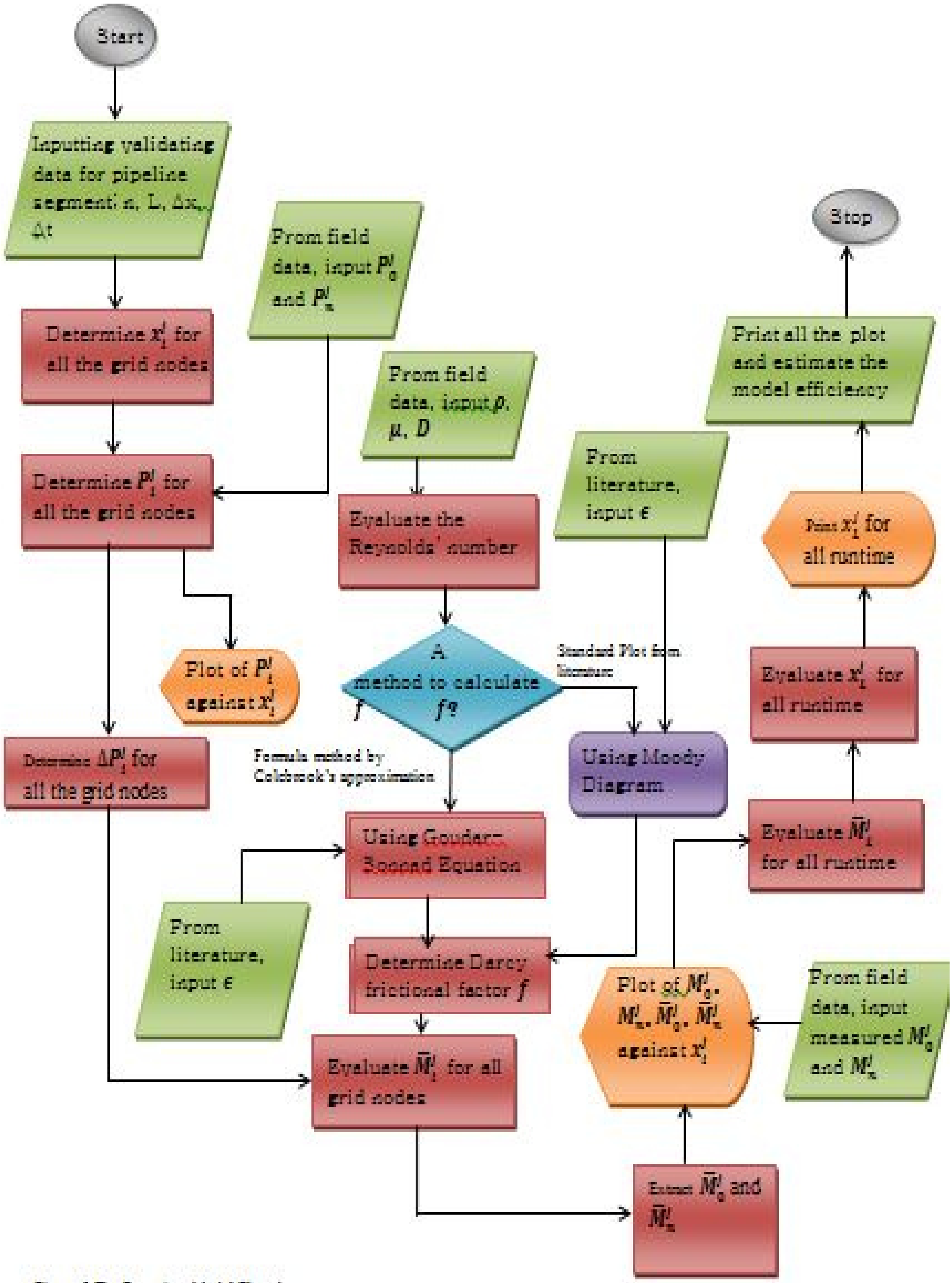

Figure 5 The Detection Model Flowchart

5. Results and Discussions

For a crude oil pipeline XY considered, the upstream temperature is about 22.05^{0}C and at the downstream end is about 20.3^{0}C. Figure 6 shows the upstream and downstream pressure trends at every time step for the MATLAB Programming.

Figure 7 shows the flow rate trends measured at the upstream and the downstream for the MATLAB

Programming.

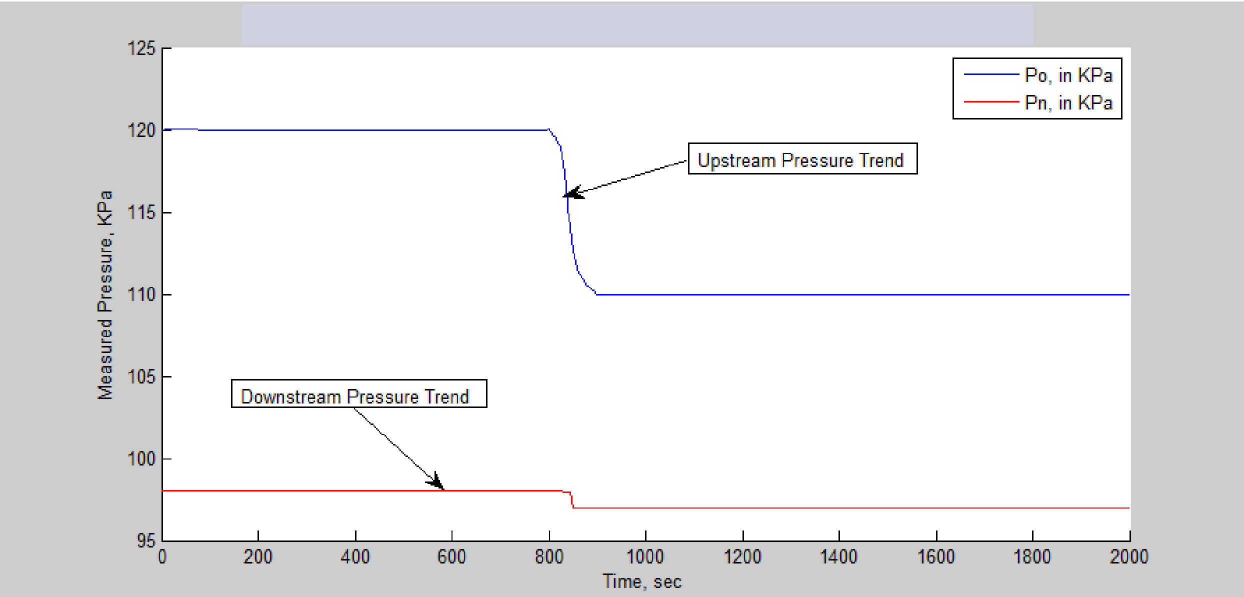

Figure 6: MATLAB Plot of Measured Upstream & Downstream Pressure Trend

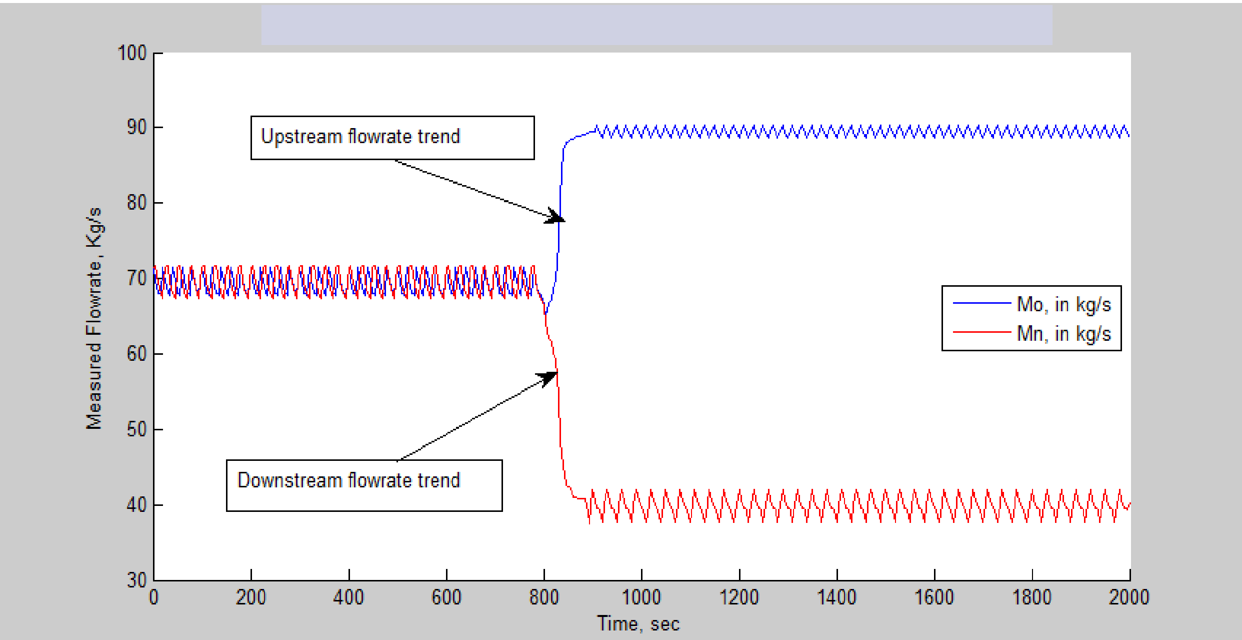

Figure 7: MATLAB Plot of Measured Upstream & Downstream Flowrate Trend

Setting the time step to 5 seconds and space step to 10metres, the pipeline model estimated the flow rates. Thus, figure 8 shows the plot of the measured flow and the estimated flow rates.

Since transiency is considered, and the pipeline configuration and fluid properties cannot all be accurate as required, it is sometimes better to keep the flowing fluid velocity as original value. From figure 8, the observed flow rates ($\overline{M_0}$ and $\overline{M_n}$) are the blue and red lines respectively while the measured flow rates (M_0 and M_n) are the green and yellow line respectively.

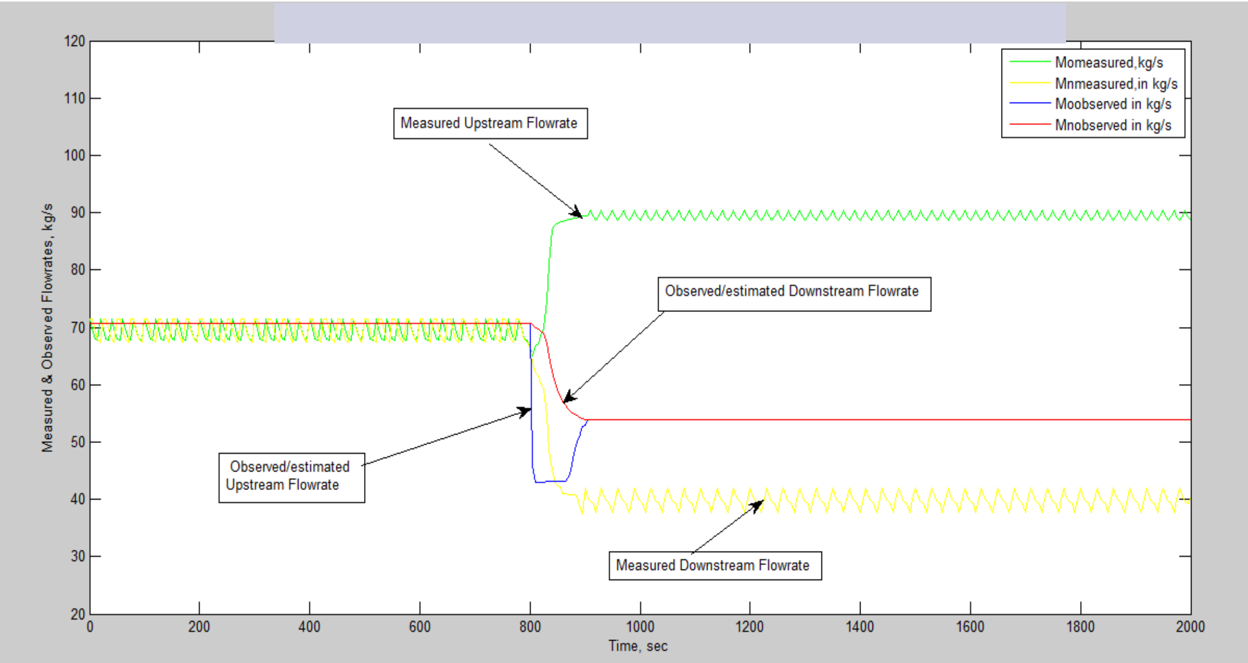

Figure 8: MATLAB Plot of Measured & Estimated Flowrates at both Upstream & Downstream Ends

At the set time interval (5 seconds), the program can make use of available data using equation 17 and the leak location was calculated as shown as the blue line in figure 9.

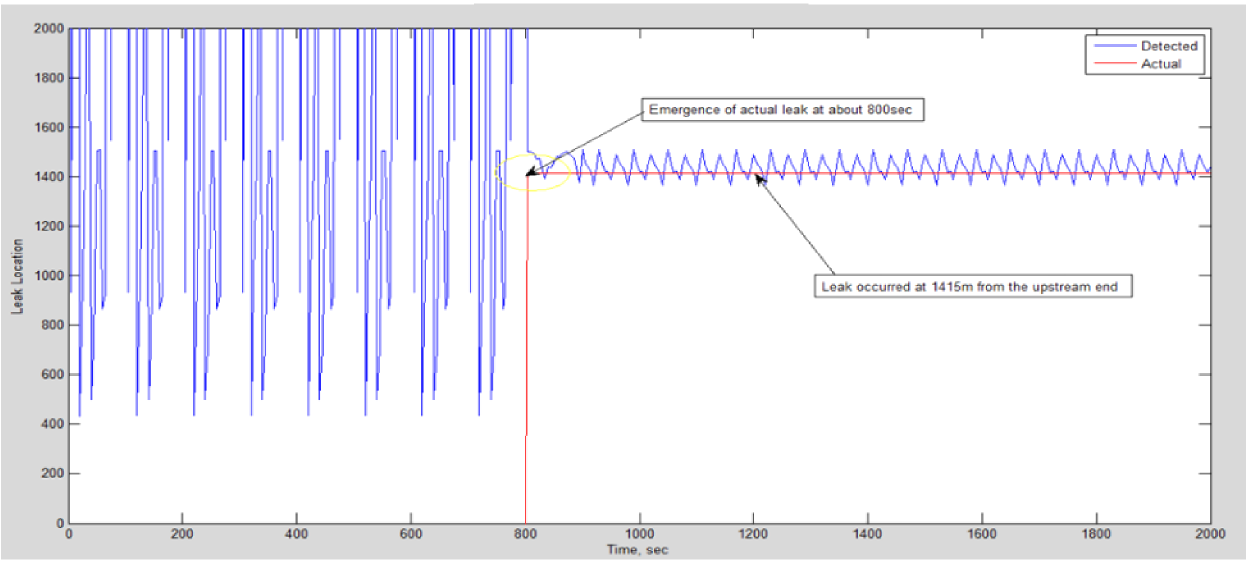

Figure 9: MATLAB Plot of Actual & Detected Leak Location

From figure 9, before the occurrence of a leak, the leak position calculated varies randomly and violently. When the leak occurs, it tends to form a sinusoidal pattern of a negligible amplitude towards the actual leak position. The red line emerging at around 800seconds shows the leak started to occur at that time to the start of the study and this shows the leak to be at exactly ***1415.0m*** from the upstream end of the pipeline. By the model, the leak is estimated to be located at ***1433.527m*** from the upstream end. After taking into consideration other factors, the leak rate is estimated as ***12.09456kg/s***.

From this analysis, the influence of pressure decline along the pipeline length was studied to have a greater effect on the leak. The leak characteristics were evaluated using the discrepancies obtained from flow rates (both measured and observed) as calculated using the pressure drop at the ends of the pipeline.

Also, Darcy-Weisbach frictional factor which was mainly used in estimating the observer's flow rates was obtained using Goudar-Sonnad equation. But also, other approximation equations of Colebrook-White Equation such as Haaland equation, Swamee-Jain equation, Serghides's equation, Brkic solution, Blasius correlation, etc. and sometimes graphical method such as Moody diagram can be used in the evaluation of the darcy frictional factor.

6. Conclusions and Recommendations

Based on the methodology employed in this paper for the diagnosis and characterization of leakages in oil and gas pipelines, the following conclusions can be drawn.

- Transient modeling for pipeline made it vast for leak to be diagnosed and quantified for a large variety of pipeline configuration.
- Leakages in pipeline will be made easy to detect during start-up or shut down.
- Transient modeling is a cheaper means of detecting leakages without the need for sophisticated computer network.

At the end of this research work, the recommendations made are as follows;

- In case of complex pipeline network or even much data involved for single pipeline, a SCADA (***S****upervisory* ***C****ontrol* ***A****nd* ***D****ata* ***A****cquisition*) network should be employed for online monitoring of the pipeline
- Since the efficiency of the model is greatly affected by the performance of the observer, provision should be made for self-adjustment in order to capture the actual system of the pipeline.
- An accurate alarming system should be provided within the SCADA network proposed to be able to account for noise signals arising from leaks.
- Flow meters and pressure transmitters should be better calibrated to improve the efficiency of the model by avoiding bias within the model.

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Appendix

At every segment i and at time index j, the segment length and pressure drop are calculated using the relations below:

$$\Delta x_i^j = x_i^j - x_{i-1}^j = \Delta x \qquad \text{A-1}$$

$$\Delta P_i^j = P_i^j - P_0^j \qquad \text{A-2}$$

From velocity profile in a pipe, the nodal average velocity exists as a parabola and can be calculated using the formula below

$$v_i^j = \frac{D^2}{32\mu} \cdot \frac{\Delta P_i^j}{x_i^j} \qquad \text{A-3}$$

The Reynolds' number to characterize the flow at segment i and at time step j of measurement is calculated as

$$(N_{Re})_i^j = \frac{\rho D \left(v_i^j\right)}{\mu} \qquad \text{A-4}$$

Using Goudar-Sonnad equation (a better and more accurate approximation equation of Colebrook-White equation), we gave the following step to get our Darcy-Weisbach frictional factor

$$a = \frac{2}{\ln(10)} = 0.868589$$
$$b = \frac{\epsilon/D}{3.7}$$
$$d_i^j = \ln(10) \cdot (\frac{N_{Re})_i^j}{5.02} = 0.458682 \cdot (N_{Re})_i^j$$
$$s_i^j = b \cdot d_i^j + \ln(d_i^j)$$
A-5a

$$q_i^j = s_i^{j\,\frac{s_i^j}{(s_i^j+1)}}$$
$$g_i^j = b \cdot d_i^j + ln\frac{d_i^j}{q_i^j}$$
$$z_i^j = ln\frac{q_i^j}{g_i^j}$$
$$(D_{LA})_i^j = z_i^j\frac{g_i^j}{g_i^j + 1}$$
$$(D_{CFA})_i^j = (D_{LA})_i^j\left(1 + \frac{(z_i^j)/2}{(g_i^j+1)^2 + ({z_i^j}/_3)(2 \cdot g_i^j - 1)}\right)$$
A-5b

Using all the constants defined in Eqn. A-5, the Darcy weisbach frictional factor can be obtained using the equation below **;**

$$(f_i^j)^{\frac{-1}{2}} = a\left[ln\frac{d_i^j}{q_i^j} + (D_{CFA})_i^j\right] \qquad \text{A-6}$$

Then after the mass flow rate at each grid node i for each time index j is given by the equation

$$M_i^j = \sqrt{\frac{\rho\pi^2 D^5(\Delta P_i^j)}{8(f_i^j)x_i^j}} \qquad \text{A-7}$$

Mathematical expectation of a random variable x which is written as E(x) is the probability of x existing on an average.

If $X = X_1, X_2, X_3, X_4, X_5, X_6, \dots, X_n$ where $X_i$sare random variables of X. if the probability of each of them are $P(X_1), P(X_2), P(X_3), P(X_4), P(X_5), P(X_6), \dots, P(X_n)$, the mathematical expectation of X is

$$E(X) = \frac{X_1}{P(X_1)} + \frac{X_2}{P(X_2)} + \frac{X_3}{P(X_3)} + \frac{X_4}{P(X_4)} + \frac{X_5}{P(X_5)} + \frac{X_6}{P(X_6)} + \dots + \frac{X_n}{P(X_n)} \qquad \text{A-8}$$

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