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Determination of Hydrocarbon Pipeline Time of Leak Using Distributed Acoustic Sensing Model

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ABSTRACT

Leak is a catastrophic incident in pipeline operations, techniques to obtain zero-delay leak occurrence is of global interest. This paper use continuity equation of fluid dynamics model and obtain actual time leak occurs in hydrocarbon pipeline. In practices, time leak occurred is not time leak observed by team of pipeline operators monitoring workstations employed to detect the leak and the swift response of the acoustic alarm in mass balance approach. The model simulated in MATLAB display high accuracy by reducing the field leak time-period drastically from 863.937 to 16.43 seconds. The model is recommended for pipeline actual time leak detection estimate.

1. INTRODUCTION

Pipeline is the fastest save means of transporting gases, liquid, and solid product. During pipeline operation, leak detection and the time the leak occurs are of primary concern to the pipeline operators. An efficient or pipeline of high integrity is the one with a very infinitesimal leak that was timely managed, quantified and controlled to obtain a negligible volume loss to the surroundings, some scholarly work has been made. Wang *et al* (2017) developed pipeline leak detection by using time-domain statistical feature of acoustic sensor characterized and identified by its waveforms, absolute amplitudes, and the frequency-domain energy distribution. Conversely the characteristics fades because of wave distortion under the condition of varying pipeline transportation. The experimental results from the field tests demonstrate the effectiveness of the actual leak time with the characterized feature extraction. Jin (2019) worked on leak detection using negative pressure wave (NPW) technique. He discovered that the Leak detection time is around the time

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required by the pressure wave to travel from the leak location to the pressure transmitter. In addition, which can provide an accurate leak location. Obibuike et al (2019) developed a mathematical model for time of leak estimation in a natural gas pipeline using pressure wave method to estimate the actual time the leak occurs in the pipeline as compare with the mass balance method, the proposed model was fast in comparison. Quy and Kim (2021) develop a work on real-time leak detection for a gas pipeline using a k-nearest neighbor (k-NN) classifier and hybrid acoustic emission features for detecting leak at a real time. To achieve the result, they develop trained k-NN classifier algorithms that are embedded on the microcontroller unit to detect leak at a real-time. The system offers a reasonable alarm triggering without a false alarm despite adding white noise input signal but yield high average classification accuracy. Javad *et al* (2022) review comparative study on computational method for pipeline leakage detection and localization at a real-time using Mass/volume balance, negative pressure wave, pressure point analysis, statistical methods, and real-time transient modeling. Their study the strength, weakness and limitation recorded a commendable result on leak location speed across a line under study. North American Energy Pipelines magazine (2022) develop the evolution of pipeline leak detection at extended real-time transient model (E-RTTM) using pattern recognitions algorithm, they made assertion that Pipeline monitoring for its integrity originated from a simple mass balance approach, for innovation of the entire systems the signature analysis technique habits leak pattern recognition to endlessly study this data and determine the pipeline's leak pattern. Conversely E-RTTM uses relative values, which continues to work effectively under turbulent pipeline conditions, without any significant effect on its sensitivity.

2. METHODOLOGY

This work is analytical model, housed by the derivative of continuity equation as a tool in fluid dynamics, it postulates that the flow area of the pipeline is directly proportional to the flow velocity. This can be mathematically representing as,

$$A \propto u \qquad (1)$$

$$R = Au = constant \qquad (2)$$

Where, R, is the volume flow rate, A, is the flow area and u, is the flow velocity.

In this paper we obtain accurate time at which the leak occurs mathematically.

To achieve the models' following assumptions are made:

i. The hydrocarbon pipeline is having a single inlet and single outlet.
ii. The fluid flowing in the hydrocarbon pipeline is non-viscous.
iii. The flow is incompressible, and the fluid flow is steady.

Understanding the Bernoulli's principle, we consider figure 1 diagram:

In this model, we consider figure 1, as the hydrocarbon flow for a short interval of time dt in the pipeline. So, assume that short interval of time as dt , at this time, the fluid will cover a distance of dx_1 with a velocity

u_1 at the sending end (inlet) of the hydrocarbon pipeline.

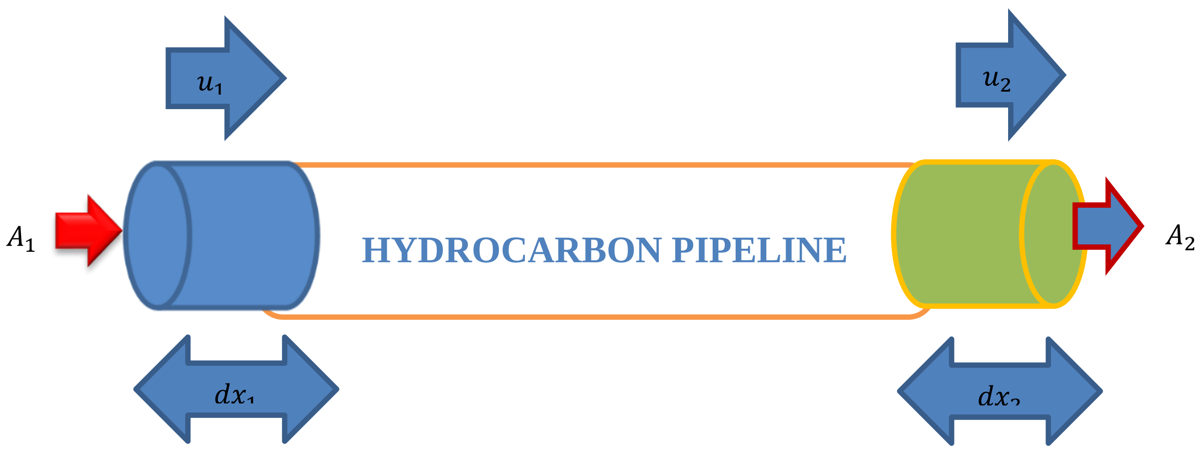

Figure 1: Simple hydrocarbon pipeline product flow diagram

At this time, the distance covered by the hydrocarbon will be:

$$dx_1 = u_1 dt \qquad (3)$$

Now, at the sending end of the pipe, the volume of the fluid that will flow into the pipe will be: $V = A_1 dx_1 = A_1 u_1 dt$ (4)

It is known that mass (m) = Density (ρ) × Volume (V). So, the mass of the fluid in dx_1 region will be:

$$dm_1 = Density \times Volume \qquad (5)$$

$$\rho_1 A_1 u_1 dt = dm_1 \qquad (6)$$

Hence the mass change at the sending end (inlet) will be

$$\frac{dm_1}{dt} = \rho_1 A_1 u \qquad (7)$$

Similarly, the mass change at the receiving end (outlet) will be:

$$\frac{dm_2}{dt} = \rho_2 A_2 u_2 \qquad (8)$$

Therefore equating 7 and 8,

$$\rho_1 A_1 u_1 = \rho_2 A_2 u_2 \qquad (9)$$

This can be written in a more general form as:

$$\rho A u = \text{constant} \qquad (10)$$

Hence, equation (10) concurs with the law of conservation of mass in fluid dynamics. Since the fluid is incompressible as it travels, the density remains constant for steady flow, therefore,

$\rho_1 = \rho_2$

(11)

Hence, equation (9) becomes:

$A_1 u_1 = A_2 u_2$

(12)

This equation can be written in general form as:

$R = A_1 u_1 = A_2 u_2 =$ constant (13)

Because the pipeline is laid horizontally; geometry involves radial motion, we adopt cylindrical coordinate configuration.

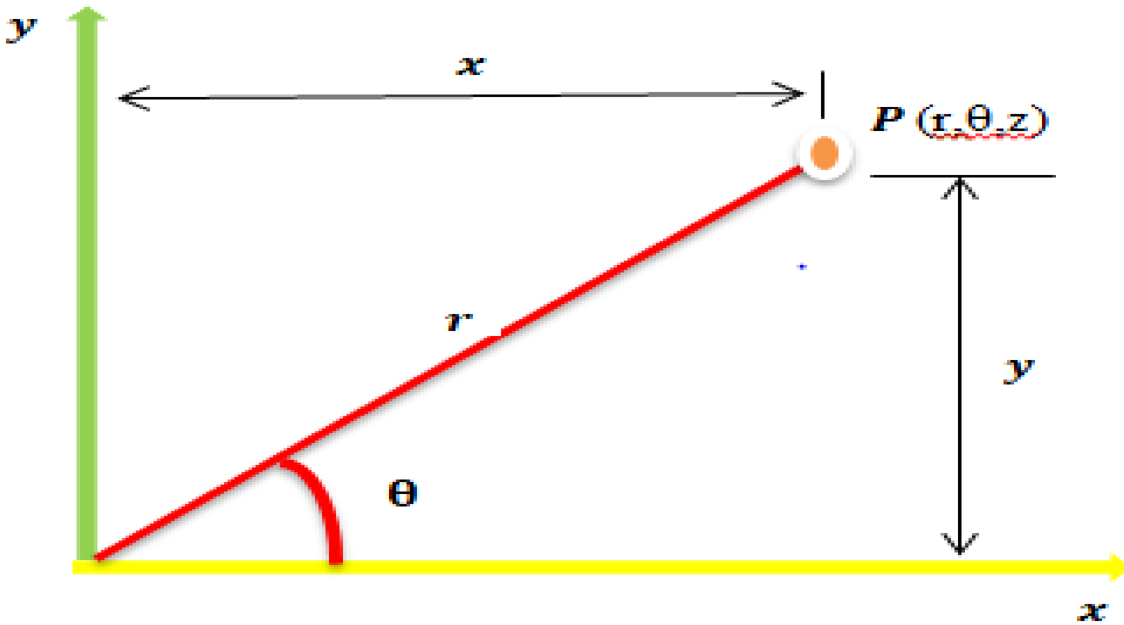

Figure 2: The model of figure 1 is a cylindrical coordinate system as fluid phase changes during flow. The velocity components in these directions are in polar form as u_r , u_θ, u_z

Equation for such model coordinates for a point P (r, θ, z)

Consequently, if the gradient operator is written as,

$$\nabla P = \frac{1}{r}\frac{d}{dr}(rP) + \frac{1}{r}\frac{d}{d\theta}(P) + \frac{1}{r}\frac{d}{dz}(P)$$

(14)

Hence the radial motion continuity equation becomes,

$$\frac{d\rho}{dt} + \frac{1}{r}\frac{d}{dr}(r\rho u_r) + \frac{1}{r}\frac{d}{d\theta}(\rho u_\theta) + \frac{d}{dz}(\rho u_z) = 0 \quad (15)$$

The equations govern the control volume analysis of an incompressible flow weather flow is steady (steady state) or unsteady (transient state).

At a steady state, the equation in three-dimensional stead flows becomes,

$$\frac{1}{r}\frac{d}{dr}(r\rho u_r)+\frac{1}{r}\frac{d}{d\theta}(\rho u_\theta)+\frac{d}{dz}(\rho u_z)=0 \quad (16)$$

Where,

ρ is the gas density, u_r , u_θ. u_z are the volumes of the velocity in three dimensions, but at a steady state of u_r

$$\frac{1}{r}\frac{d}{dr}(ru_r)=0 \quad (17)$$

Hence flow in u_r – direction becomes,

$$\frac{d}{dr}(\rho u_r)=0 \quad (18)$$

Equation (18) becomes possible when there is no mass accumulation.

Hence integrating with respect to r

$$\rho u_r = constant \quad (19)$$

Using equation (2).

$$\rho A u = \rho A u_r = constant \quad (20)$$

Consequently

$$\rho_1 A_1 u_1 = \rho_2 A_2 u_2 = \frac{dm_1}{dt} = \frac{dm_2}{dt} = 0 \quad (21)$$

It is mass rate in the inlet pipeline minus the mass rate out pipeline.

$$M_{inlet} - M_{outlet} = 0 \quad (22)$$

$$M_{inlet} = M_{outlet} \quad (23)$$

$$\rho_1 A_1 u_1 - \rho_2 A_2 u_2 = 0 \quad (24)$$

Therefore, when there is leak the equation becomes,

$$M_{inlet} - M_{outlet} = M_{LEAK} \quad (25)$$

The figure 3 shows the unaffected fluid flow distance (D) and affected fluid part (E) with the total distance of the pipeline length (L) used for the bench setup to capture Nigeria Gas company (NGC) hydrocarbon pipeline I.D lines. Thus, in this model, we considered it as a horizontal pipeline of equal cross-sectional area transporting hydrocarbon at steady rate isothermal condition and understand that leak detection time is not the same time the leak occurs in the pipeline, thus,

T_L, is the time the first mass of fluid exits the leak opening (time of leak). T_O, is the time the leak was observed by the pipeline monitoring team

t_p , is the time-period between when the leak occurred and when it was detected

Mathematically the above assumption is express as; $\{T_L\} < \{T_O\}$

If M is a fluid mass without leak through the pipeline, then when leak occurs the mass of fluid loss M_L at a time interval between when the leak occurred and when it was detected is.

$$t_P = (T_O - T_L) \quad (26)$$

The T_O is a human time given by the monitoring team at the workstation, hence if we have t_p as the time interval period between when the leak occurred and when it was detected, then we calculate the time of leak T_L as,

2.1. The time of leak model architecture.

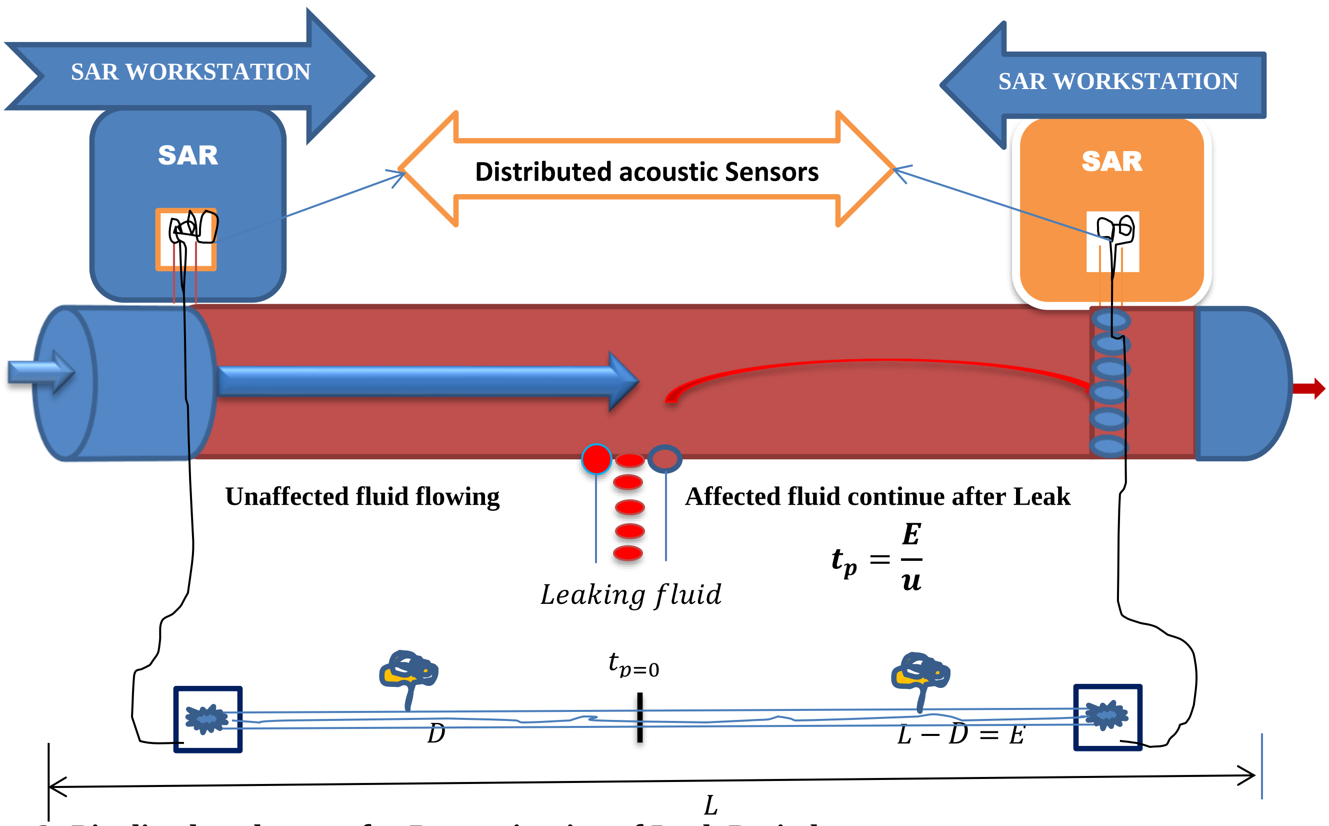

Figure 3: Pipeline bench setup for Determination of Leak Period

$$t_P = (T_O - T_L)$$

Recall that the distance travelled by the fluid from the sending end to the receiving end is given as Velocity x Time = Distance

To satisfy the interest of the work (Time of leak determination using DAS) we have,

$$L - D = E \qquad (28)$$

As the distance travelled by the fluid, from the sending end to the receiving end is identified as the affected part as shown in figure 4.

Thus. (27)

$$u = \frac{E}{t_P} \qquad (29)$$

Equation (29) is a general equation for time of leak used in this paper

Consequently, using equation (2) and (10), the flow rate of the affected hydrocarbon R_D documented at the exit point is given by the equation as,

$R_D =$
uA (30)

u is the velocity of the hydrocarbon travelling downstream to the output of the pipeline, m/s
A , is the cross-sectional area of the pipeline.
Combining equation (29) with equation (30), it can be rewritten as.

$$R_D = \left(\frac{E}{t_p}\right)\frac{\pi d^2}{4} \quad (31)$$

However, cross-multiplying and making t_p a subject of the formula, it becomes,

$$t_p = 0{,}785d^2 \left(\frac{E}{R_D}\right) \quad (32)$$

Hence, the actual time the leak happened is T_L , and is equal to the time leak was observed and documented is T_O , minus the time-period t_p it happened as deduced in equation (26) and was rewritten as,

$$T_L = T_O - t_p \quad (33)$$

2.2. Leak period determination using DAS model

Due to high rate of false alarm involves on the use of mass balance method in resolve of leak period, we proposed distributed acoustic sensing that uses the principle of sound wave during leak, when leaks occur, sound wave is emitted, such wave is detected by optic fiber sensors, comes as alarm system and travels along the pipeline parts. Hence equation 29 is the velocity of the acoustic wave V_{AW}traveling along the pipeline body. Thus, the equation becomes.

$$t_p = \frac{L-D}{u_{sw}} \quad (34)$$

Given that velocity of the sound wave along the medium of a steel pipe wall is 5960 m/s which helps to implement equation 34 and in turn calculate the time of leak (T_L) since the monitoring team can provide the time the leak is observed (T_O) from equation 33

2.3: Time of leak model simulation

The result in time of leak simulation were obtained in two techniques, the mass balance as used by many authors shown in equation (26) and the proposed model using sound wave of distributed acoustic sensing as shown equation (33) in determination of time of leak.

3. RESULT AND DISCUSSION

3.1 Result of time of leak using mass balance techniques

This table 1, shows a leak time profile of the mass balance with acoustic alarm systems used by the monitoring team, at different line ID that represent different length of pipeline incident under operation. Though it is a field data but equation (29) and (33) satisfy the leak period recorded by the team of operator with errors of human factor and instrument (false alarm) that will be addressed by the proposed model.

Table 1: The Leak time profile of mass balance field data

Line ID	**Leak period (t_p)mins**	**Time leak was Recorded (t_O)**	**Actual time of leak occurred (T_L)**
L25	15.0101	01:30am	01.15am
L8	05.0012	05:40am	05.35am
L31	12.2540	12:09am	11.57am
L32	08.3004	03:16pm	03.08pm
L33	11.4021	08:52pm	08.41pm
L34	08.1202	12:50am	12.42am
L30	06.2013	07:53am	07.47am
L28	19.2001	03:05pm	02.46pm
L10	44.1012	08:09am	07:25am

3.2. *The results for Time of Leak Using distributed acoustic sensing (DAS) Method*

Table 2: Time of leak simulation result using the proposed model

Line ID	Pipeline length [km]	Distance of Leak location (L_P) [km]	Leak period (t_P) mins
L25	50	11.09	0.1088
L8	44	15.71	0.0791
L31	90	17.60	0.2025
L32	99	21.22	0.2175
L33	91	12.85	0.2185
L34	105	11.62	0.2611
L30	196	1.38	0.5442
L28	196	6.18	0.5308
L10	128	19.95	0.3022

The Table 2 used equation (34) as it affects the study to simulate leak period (t_P) of different pipeline length and distance of leak location point (L_P) using 357.6km/minutes as a speed of sound in a solid (steel pipeline). The result recoded leak period mean value ($\bar{x}$) of 0.2738 minutes or 16.43 seconds.

Table 3: Leak period ((t_P) comparison of acoustic wave sensing and mass balance approach

Line ID	**Pipeline length [km]**	**Distance of Leak location (L_P) [km]**	**Mass balance approach Leak period (t_p)mins**	**Distributed Acoustic wave sensing approach Leak period ((t_P) min**
L25	50	11.09	15.0101	0.1088
L8	44	15.71	05.0012	0.0791
L31	90	17.60	12.2540	0.2025
L32	99	21.22	08.3004	0.2175
L33	91	12.85	11.4021	0.2185
L34	105	11.62	08.1202	0.2611
L30	196	1.38	06.2013	0.5442
L28	196	6.18	19.2001	0.5308
L10	128	19.95	44.1012	0.3022
Total			127.5906	2.4647
Mean value			14.3990 mins or 863.937 sec	0.2738 mins or 6.43 sec

The table 3 leak period simulation result was compared using acoustic wave signal during leak, it shows a mean value ($\bar{x}$) of 0.2738 minutes or 16.43 seconds against 14.3990 minutes or 863.937 seconds of mass balance approach. The inference drawn, shows high mean value reduction of leak period detected with the proposed model when compare with mass balance techniques, which satisfies that sound wave travel faster than the fluid in the pipeline and consolidate the use of the model to verify the actual leak period in pipeline operation without shutdown of the system under operation.

4. CONCLUSION

The mathematical equations were developed analytically to obtain the time of leak in hydrocarbon pipeline of different line ID of Nigerian gas company (NGC) under monitor with mass balance technique, the model results indicate the flux between the time the alarm trigger for the leak occurrence and the actual time the leak occurs are not the same. The mean value leak period difference between mass balance approach and acoustic wave sensing shows the model (acoustic) effective nature on triggering the alarm for time of leak accuracy and sensitivity. The longer time of the alarm files for false alarm error and inefficient nature from the fluid exit time to the time the monitoring team detected the exit. For absolute pipeline high integrity monitoring of hydrocarbons, the model will fine its use in several places such as SAR, SCADA, and RAR workstations. More so, where human habitations leave at the pipeline right of way, loss of live and properties on much delay in time of leak detection will be high, catastrophic when not addressed and the volume loss will retard the economic growth contributed by such product pipeline.

Reference

Javad S., Seyed H. H., and Masoud S., (2022). Computational methods for pipeline leakage detection and localization: A review and comparative study, Journal of Loss Prevention in the Process Industries, Volume 77, ISSN 0950 4230, https://doi.org/10.1016/j.jlp.2022.104771.

Jin Mingang (2019). Investigation on Parameters Affecting the Performance of Negative Pressure Wave Leak Detection Systems.Paper prepared for presentation at the PSIG Annual Meeting held in London, England.

North American Energy Pipelines *magazine is a free trade publication for industry professionals*, 2022, August 3-4

Obibuike U. J., Ekwueme S. T., Ohia N. P., Igbojionu A. C., Igwilo K. C. and Kerunwa A., (2019).. Mathematical Model for Time of Leak Estimation in Natural Gas Pipeline. Petroleum Science and Engineering.3(2): 68-73. doi: 10.11648/j.pse.20190302.15

Quy T.B. and Kim J.M., (2021). Real-Time Leak Detection for a Gas Pipeline Using a *k*-NN Classifier and Hybrid AE Features. MDPI Sensors (Basel) doi: 10.3390/s21020367

Schlumberger. (2014). OLGA Dynamic Multiphase Flow Simulator. http://www.software.slb.com/products/foundation/Pages/olga. Aspx

Wang, F, Lin, W, Liu, Z, Wu, S and X. Qiu, (2017)."Pipeline Leak Detection by Using Time-Domain Statistical Features," in IEEE Sensors Journal, 17(19): 6431-6442, doi: 10.1109/JSEN.2017.2740220

List of nomenclature

NPW- Negative Pressure Wave
k-NN- k-nearest neighbor
E-RTTM- Extended Real-Time Transient Model
R - volume flow rate
A - flow Area
u - flow velocity
dt – short interval of time
dx_1 – Distance fluid cover relative to the inlet
u_1 – velocity relative to inlet of the pipeline
V- volume of the fluid flowing in the pipeline
ρ- Density
m-mass
dm_1- mass change at the inlet
dm_2- mass change at the outlet
u_r , u_θ, u_z – the velocity component in polar form
P (r, θ, z)- Coordinates for a point P
M_{inlet}- mass rate in the inlet pipeline
M_{outlet}- mass rate in the outlet pipeline
SAR- synthetic aperture radar
SCADA – supervisory control data acquisition
RAR- Real aperture radar
D- unaffected fluid flow distance
E-affected fluid part
L-total distance of the pipeline length
NGC- Nigeria Gas company
T_O- Observed Leak time
T_L-Time of leak
t_p-Time period the leak occurred
L_P-Distance of Leak location point (L_P) [km]
R_D- flow rate of the affected hydrocarbon documented
u_{sw}-velocity of the sound wave along the medium of a steel pipe wall is 5960 m/s or 364.9km/min.
($\bar{x}$) – mean value.