A NEW BUNKERING TECHNIQUE IN GAS PIPELINE IN NIGERIA: A NOVEL LEAK DETECTION APPROACH

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ABSTRACT
Oil and gas pipeline theft popularly called "bunkering" has drastically affected Nigeria economy which is solely dependent on oil. People usually break the pipeline and siphon huge quantities of crude and sell it in the black market at a much lower price. Though, a lot of technique has been developed to detect and localize leakages in pipeline on time to prevent theft and spillage, a new technique is now being used in Nigeria to siphon gas from pipeline without being easily detected. We discovered from the simulation result using **modified panhandle B equation** that if during pipeline down time or induced down time due to sabotage from pipeline staffs, that if a long and wide host is forged into a pipeline for gas theft, the change in flow rate is unchanged or infinitesimal that control room engineers term it **'small leak'** when huge quantities of gas is being taken away from the pipeline. It is a novel leakage detection technique in natural gas pipeline.
Keywords: Pipeline leak detection, Gas theft/Bunkering, Panhandle B equation, Pipeline vandalism, Pipeline leak localization, small leak.

1. INTRODUCTION

Monitoring pipeline networks is of immense concern to pipeline operating companies because of the heavy economic loss and catastrophic effect of leaks that may occur. Efficient leak monitoring and localization is therefore an integral part of pipeline structural integrity due to development of leaks caused mainly by corrosion and pressure surge. According to [1] pipelines are the safest means of oil and gas transport even though they are most often not risk free. The major causes of pipeline accidents are; external interference, corrosion, construction defects, material failure and ground movement [2]. Owing to a number of gas pipeline leakages reported in literature, especially [3], large pipelines (ie, with a length of 800 miles or more) can expect at least one reportable leak-related incident per year. Thus, there is an urgent need for pipeline operators to be on alert to checkmate pipeline leakages. Many literature have classified gas pipeline leakages in variant ways. [4] classified leakages based on the degree of human aid or intervention needed for the system to function effectively. Those that does not require human operations are automated. Those that require a certain amount of aid from humans are semi-automated while those that rely completely on humans are manual detection. Scott [5] classified detection into hardware based and software based methods. [6] identified the third technique as the biological method. Biological method involves using trained dogs or experienced personnel to detect and locate a leak by visual inspection, odour or sound. This biological technique is also called non-technical method [4].

Hardware based leak detection systems include pigging [7], acoustic methods [8][9], tracer gas methods[10], sensor cable method[11], fiber optic methods[12], infrared photography methods[13], and radar methods[14].They all use devices for leak detection and localization.

Leaks on pipelines always produce sound or acoustic noise that are picked up by acoustic sensors mounted on the pipelines at some distance from one another[15].The comprehensive review of acoustic sensors is given by Loth[16]. Kim[17] and [16] using a time-frequency technique and the low frequency impulse respectively detected leakages in gas pipelines based on measurements from two acoustic sensors mounted on each end of the pipe. Meng[18] in order to increase leak detection accuracy adapted the leak location formula. Optical hardware method of leak detection are divided into two categories viz active and passive[19]. While active method requires radiation source for monitoring leakage, passive does not. ITT corporation[20] opined that all optical techniques involve using aircraft-mounted optical devices for aerial survey of natural gas networks for leakage detection. This aerial mapping provides an overview of overall pipeline networks, thus aiding localization much faster than any ground monitoring with handheld devices. All active optical methods uses similar technique of assuming leakages when there is significant scattering or absorption of radiation by natural gas molecules above a pipeline[4].Some active methods are; light detection and ranging(LIDAR)[21], diode laser absorption(DLA)[22], and millimeter wave radar systems(MWRS)[23], to mention only a few. LIDAR and DLA are similar in operation. While LIDAR uses expensive pulsed lasers to monitor the absorption of laser energy, DLA uses diode lasers that are less expensive. MWRS are based on the radar signature of the area above the gas pipelines.

Optical fibers are optical and communication monitoring technique. The change in ambient temperature of surrounding pipelines due to gas leaks escaping the pipeline is detected by optical fibers located at the vicinity of pipelines [24]. Thus, they monitor a series of physical and chemical properties [25]. The passive detectors include thermal imaging[26], multi-spectral imaging[27] and gas filter correlation radiometry[28].

In soil monitoring hardware technique, the gas pipeline is inoculated using a non- hazardous tracer compound[29] which is highly volatile and exit the pipe in the exact location of the leak when it occurs. Praxair technology[30] recommended that to detect leak, field instrumentation is used to monitor pipeline surface by moving the device along it. In vapor sensing, sensor tubes are buried along the pipeline[31].This sensor tubes collect diffused gas in event of a leak and the vapors are sampled and analyzed. The concentration of the hydrocarbon vapors is used to estimate the size of the leak.

Software based methods use various computer software packages to detect leaks in a pipeline. Some of the software techniques are; mass/volume balance, real time transient modeling, negative pressure wave, statistical method, and digital signal processing[4]. The mass/volume balance is based on the principle of conservation of mass where leak is detected when there is discrepancy between inflow and outflow measurements[32][33][34].Usually, a leak alarm is generated when such imbalance exists using the readings of some computed process variables such as flow rate, pressure and temperature. The real time transient modeling makes use of mathematical pipe flow models like the conservation of mass/momentum/energy. The presence of a leak is predicted when there is discrepancy between measured and predicted values[4]. [35] used this technique first in which they designed an observer in conjunction with friction adaptation that generate an output different from the one obtained from measurements in the event there is a leak. Negative pressure wave rely on assumption that a leak is practically associated with a sudden pressure or flow drops in the pipeline. This drops at the location of the leak is propagated both upstream and downstream as negative pressure wave or longitudinal (rarefaction) wave and are recorded using pressure sensors mounted at both ends of the pipelines [36]. The time difference between the receptions of this wave by the two end transducers is used in localizing the leak. Atmos wave [37] negative pressure wave leak detection systems cannot only localize the leak but also estimate the size of the leak. The pressure point analysis is a fast technique requiring continuous measurements of pressure in different points along the pipeline. A fall in pressure inside the pipeline below a predefined threshold indicate the presence of a leak[38]. The statistical method employs advanced pattern recognition functions to flow and pressure measurements in a pipeline. Variations generated by operational changes are registered and a leak alarm is generated only when a unique pattern of changes in flow and pressure exists[6]

This work uses dynamic modeling approach where a leak in pipeline is detected by drops in flow rates. The fluid flow is by steady state gas flow equations and leakage detection is using modified panhandle B equation.

2. METHODOLOGY

2.1 PIPELINE DESIGN, EQUATION AND MODELLING.

The simplest way to convey a fluid is by means of a conduit or pipe. The minimum basic parameters that are required to design the piping system include, but are not limited to, the following; the characteristics and physical properties of the fluid, the desired mass-flow rate (or volume) of the fluid to be transported, the pressure, temperature, and elevation downstream/upstream, the length of pipeline and equivalent length (pressure losses) introduced by valves and fittings. Although piping systems and pipeline design can get complex, the vast majority of the design problems encountered by the engineer can be solved by the standard flow equations[39].

2.2. PRESSURE DROP FOR GAS FLOW

The general equation for calculating gas flow is stated as;

$$Q = cED^n \left[\frac{T_s}{P_s}\right]^u \left[\frac{(P_1^2 - P_2^2)}{S^x LTZ}\right]^y \qquad (1)$$

P_1 and p_2 =upstream and downstream pressures in psia, ie pounds per square inch absolute
For Panhandle B, c=30.7083, n=2.53, u=1.02, x=0.961, y=0.51;
D=Pipe inside diameter and L=Pipeline length in Mile
E=efficiency factor. It is 1.0 for new pipes, 0.95 for good working condition, 0.85 for old pipes.
Q=Volumetric flow rate in cfh, ie, cubic feet per hour.
S=specific gravity of gas in pipeline relative to air. It is unit less.
T= Absolute temperature in Rankine
V=Velocity of gas = Q/Aand Z=gas compressibility factor.
p = Greek letter rho. Density in lb/ft^3, i.e. pounds per cubic foot.

Subscripts: s = Standard conditions (520 R, 14.73psia). T_S =520R, P_S =14.73psia

The general equation above is for horizontal pipes. For vertical pipes, the correction for the static head (H_c) of fluid is incorporated into equation 1 as follows;

$$Q = cED^n \left[\frac{T_s}{P_s}\right]^u \left[\frac{(P_1^2 - P_2^2 - Hc)}{S^x LTZ}\right]^y \qquad (2)$$

$$H_c = \frac{0.0375 g (H_2 - H_1) P_a^2}{Z\, T_a} \qquad (3)$$

$T_a = Average\ temperature\ (oR)$
$P_a = Average\ pressure\ (Psia)$

2.3 PRACTICAL EQUATIONS FOR GAS FLOWS IN PIPELINE

The Weymouth, panhandle A and panhandle B equations are used for practical pipeline purposes. The Panhandle A was developed in the 1940s and Panhandle B in 1956[40]. According to crane [40], If the pressure drop in a pipeline is less than 40% of inlet pressure, Darcy-Weisbach incompressible flow calculation may be more accurate than the Weymouth or Panhandles for a short pipe or low flow. The Darcy equation is valid for any flow rate, diameter, and pipe length, but does not account for gas compressibility. If the pressure drop is less than 10% of P_1 and you use an incompressible model, then the gas density should be based on either the upstream or the downstream conditions.
If the pressure drop is between 10% and 39%, then the density used in an incompressible flow method should be based on the average of the upstream and downstream conditions. If the pressure drop exceeds 40% of P_1, then use a compressible model, like the Weymouth, Panhandle A, or Panhandle B[40]

2.4 PANHANDLE B EQUATION

This equation is used for moderate-Reynolds-number flows where the Moody friction factor is independent of relative roughness and is a function of Reynolds number to a negative power. It is recommended for long runs of pipe such as cross-country transmission pipelines, moderate Reynolds numbers, inlet pressure greater than 1000psia and change in pressure greater than 40 percent inlet pressure[40].This equation is used in large diameter, high pressure transmission lines. In fully turbulent flow, it is found to be accurate for values of Reynolds number in the range of 4 to 40 million[41]. Substituting c, n, u, x and y, of equation 1 and dividing by 10^6 gives Panhandle B equation.

$$Q = 0.0208E \left[\frac{P_1^2 - P_2^2}{S^{0.961} ZTL}\right]^{0.51} * D^{2.53} \qquad (4)$$

The equivalent frictional factor (f)

$$F = \frac{4}{(16.49 Re^{0.01961})^2} \qquad (5)$$

2.5. MODIFICATION OF PANHANDLE BEQUATION FOR LEAK DETECTION IN PIPE

The cranes postulation that if Change in pressure is greater than 40%P_1, then Panhandle B is suitable, is used to modify equation 4 above for leakage detection.

$$\Delta P \geq 40\% P_1$$

$P_2 = 0.6P_1$; Substituting into (4), the panhandle B becomes

$$Q_1 = 0.028E\left[\frac{0.64P_1^2}{S^{0.961}ZTL}\right]^{0.51} * D^{2.53} \qquad (6)$$

The pipe in Fig1 is opened as shown in Fig2 and a pipe (host) is inserted for oil and gas bunkering or theft.

For the inserted pipe/host, the flow rate is given by

$$q = 0.028E\left[\frac{P_2^2 - P_3^2}{S^{0.961}ZTx}\right]^{0.51} * d^{2.53} \qquad (7)$$

d = diameter of the inserted pipe/host/leak, and x = thickness of leak or length of inserted pipe/host on the pipeline. Similarly,

$P_3 = 0.6P_2 = 0.36P_1$

The overall flow rate with a leak is now given by

$$Q = 0.028E\left[\left[\frac{0.64P_1^2}{S^{0.961}ZTL}\right]^{0.51} * D^{2.53} - \left[\frac{0.2304P_1^2}{S^{0.961}ZTx}\right]^{0.51} * d^{2.53}\right] \qquad (8)$$

This is the modified panhandle B equation for leak detection in gas pipeline.

3. SIMULATION PARAMETERS FOR NATURAL GAS (METHANE)

The following data were used in the simulation:

- The **Natural gas** used for this study is **methane** because it consists of **95%** composition of natural gas. Any other natural gas would have given similar result.
- The material in use globally for natural gas pipeline design is **carbon steel** with internal diameter D =2-60 inches (51-1524 mm).
- For this work, pipe internal diameter **D=1219mm=48inchs** is used. This is because in [42], the most common pipe diameter in use in Nigeria is (838mm=33inch), followed by 1219mm=48 inches. D=1219mm was selected because the panhandle B uses D =36inches or above.
- Pipe efficiency **E=0.85**.This is because in [42], most pipeline in use in Nigeria is ageing. It is 0.95 for pipes working normally, 1.0 for new pipes and 0.85 for old pipes.
- For panhandle B, inlet pressure must be greater than 1000psia. **p_1=1200psia** is used in this work. Any other value above 1000 would have given similar result.
- Density, compressibility factor (Z), and temperature (T) for methane were taken from **NIST REFPROP 7 DATABASE** [43].The specific gravity(S) is calculated as;

$$S = \frac{density\ of\ gas}{density\ of\ air} \qquad (9)$$

At T = 25°C and P = 1atm or 14.696 psia

Density of air = 1.1840psia

Density of Methane =0.6569psia,

S= 0.5548; Z=0.9982 and T= 25°c= 77°F= 536.6°R;

The pipeline is simulated using Matlab as follows;

(a)The variation of pipeline length (L) with flow rate at full capacity with internal diameter (d) of the leak kept at 0,ie no leak is shown in Fig3.

(b)The thickness of the leak(x) is kept constant at 0.4mile and the leak diameter(d) is varied at pipeline lengths(L) of 10mile,20mile,and 30mile.The variation of flow rates with leak diameter is shown in Fig4.

(c)The length of the pipeline(L) is kept constant at 20mile and the leak thickness or preferably the inserted pipe/host length(x) is varied. The variation of flow rates with leak thickness at leak diameters of 10inch, 20inch, 30inch and 40inch is shown in Fig5.

4. RESULTS AND ANALYSIS

(a) The simulation results in Fig3 shows that as the length of pipeline increases, the gas flow rate decreases. This is true practically since flow rate is inversely proportional to pipeline length.

(b) Fig4 shows that as leak diameter increases, the flow rate decreases and this decrease is more pronounced as the pipeline length increases. Thus with leaks, the flow rate decreases proportionately.

(c)Fig5 shows a special case where gas leakage is by sabotage/theft otherwise called bunkering. It shows that if pipeline is opened, may be during downtime, and a long and wide host/pipe is inserted to tap gas, as the host length and leak diameter increases, the flow rate drops abruptly and immediately appreciates. The pipeline engineers may attribute such to pressure or flow surge or even operational faults when large quantities of gas is being stolen from the pipeline. At a lower leak diameter of 10inch, there is little or no change in flow rates. The control room pipeline engineers may think that the leak is very small or may not notice any change in flow parameters at all. This is the major breakthrough in this work. Thus, when a large hole is made on a pipeline and a long host is used to tap oil or gas from the pipeline, the engineers in the control room may not know that a large volume of gas is being diverted, hence the need to be on alert when any of the flow parameter changes no matter how small.

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5. CONCLUSION

Pipeline control room engineers should not treat with levity any small change in flow parameters eg volume and mass flow rates, pressure changes etc. If there is a sudden change in flow parameters and an instant appreciation, one should suspect a wide and long host/pipe forged on the pipeline. In Nigeria, this is done as a coordinated/organized sabotage

A coordinated sabotage is an illegal operation where pipeline vandals in collaboration with pipeline staffs induce downtime on the pipeline and insert a pipe for gas theft. They normally take the pipe to a secluded place where they siphon oil for months without people knowing. If the hole on the pipeline is small, the theft may continue forever without anybody knowing. Fig5.

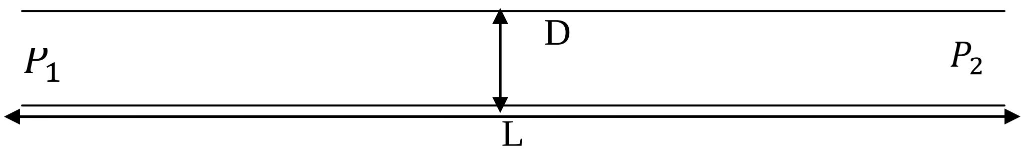

Fig1: Pipeline showing inlet and outlet pressure

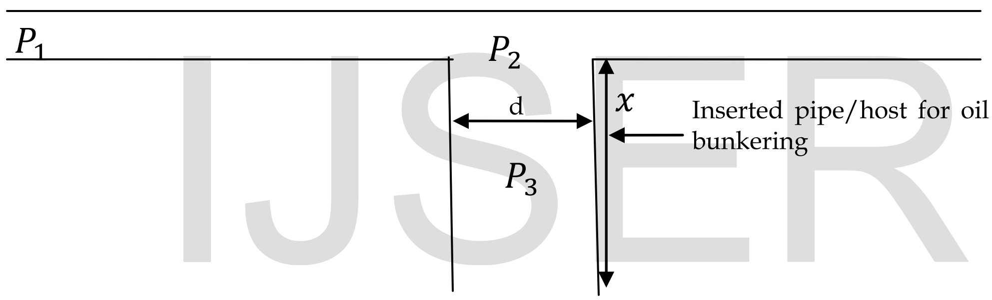

Fig2: pipeline showing a leak with thickness or inserted pipe length x

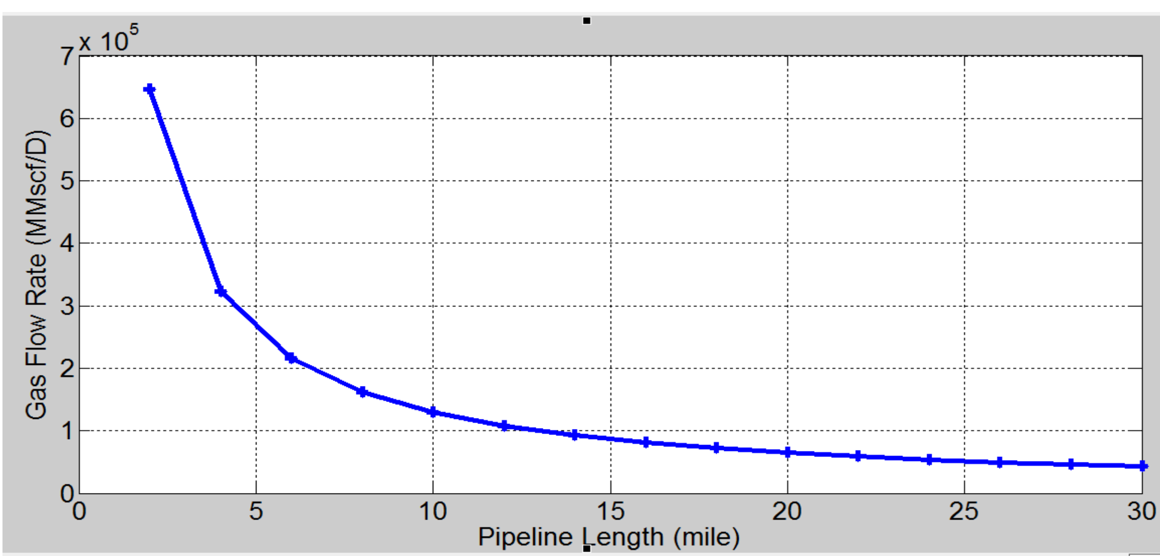

Fig 3: Graph of gas flow rate(Q) vs pipeline length(L)

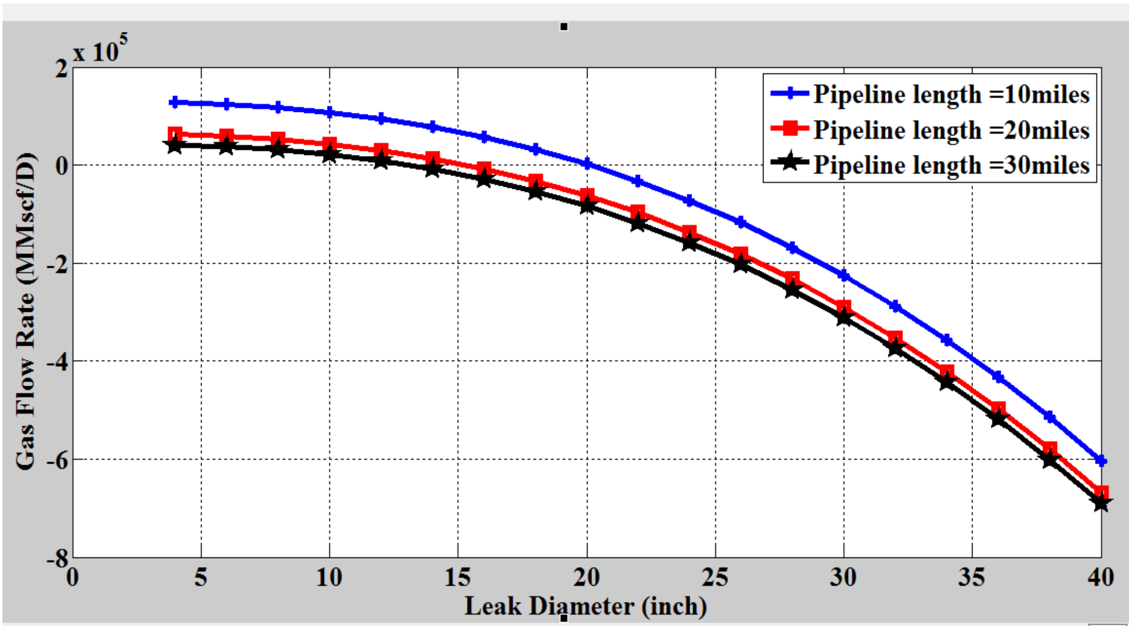

Fig4: Graph of flow rate (Q) vs leak diameter (d) for different pipeline lengths at constant leak thickness/inserted pipe length, x = 0.4mile

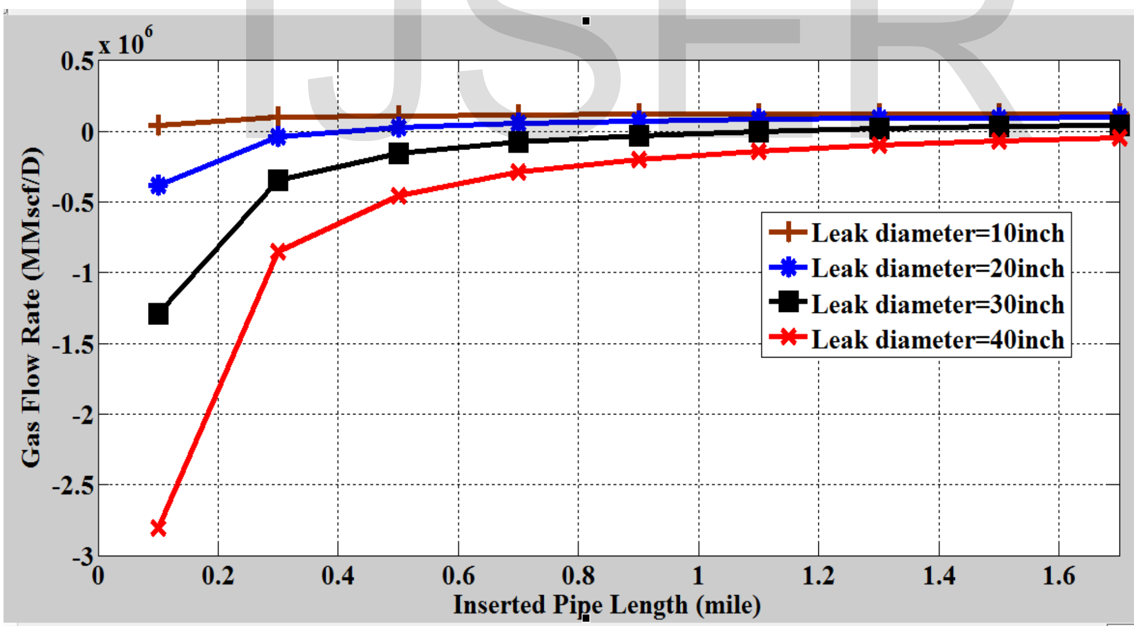

Fig5: Graph of Gas Flow rate (Q) vs inserted pipe length/leak thickness(x) for different leak diameter at constant Pipeline length, L =20mile.

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