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Estimation of Gas Leak Volume to Quantify Gaseous Fluid Flow in Processing Plants

***[1]USIABULU, GI; [1,2]OGBONNA, J; [1,2]AIMIKHE, V; [1,2]OKAFOR, E; [1,3]NOSIKE, L**

**[1]World Bank Africa Centre of Excellence, Centre for Oilfield Chemicals and Research, University of Port Harcourt, Port Harcourt, Nigeria*
[2]Department of Petroleum and Gas Engineering, University of Port Harcourt, Port Harcourt, Nigeria
[3]Integrated Elvee Services Ltd, Enugu, Nigeria

**Corresponding Author: Email: godsdayusiabulu@gmail.com*

ABSTRACT: Leak detection based on volume changes is common in conventional liquid processing systems, but present challenges in gas systems. This paper estimates the gas leak volume to quantify gaseous fluid flow in processing plants using prior-calibration-relation techniques. The estimation of volume following this pressure-based model requires that the pressure indicator of the gas leak is normalized against the initial volume before the pressure drop. Normalization makes it possible for equivalent pressure and gas volume data to be presented in percentage or fraction, so they are comparable. (This is similar to the pressure reading or drop on the regulator gauge of a gas cylinder, which is proportional to the equivalent gas cylinder weight or volume difference due to the depressurisation) An example of leak estimation for Gas Plant JK – 52 real-time test case modelling is shown in this work. The change in pressure dP was plotted against the change in volume dV in a prior calibration to derive a relationship between dP and dV. For a Pressure drop of 5 bars, Leak Volume = 2.40 m3 or 84.7 scf of gas. Such estimation of actual gas volume is useful in tying gas leak to environmental impact, HSE and in costing of economic loss.

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Keywords: estimation of gas leaks; fluid normalisation; depressurization; gas processing plants.

Gas leaks are invisible, unregulated and majority go unnoticed. These leaks may depend on any of the following: operation practices, equipment age and maintenance. Leaks and venting at natural gas processing plants release other pollutants (e.g., benzene, hexane, hydrogen sulfide) besides methane that can threaten air quality and public health. Hence, there is need for early detection of gas leaks by using appropriate Machine Learning models. Nigeria is a province of gas with pockets of oil (Teriba, 2018), and the use of pipeline is considered as a major means of conveying petroleum products which serves as the major assets to the Nigeria economy and should well protected. Gas leaks are significant hazards in several industry segments and especially in the oil and gas industry, where large volumes of highly explosive gases are transported, treated and stored. The consequences of gas leaks may be catastrophic to both life and investments. The industry and the society work together and develop efficient methods to find and minimize leakages of gas to the atmosphere also due to environmental reasons. Gas processing plant operators searching for leaks with photoionization detectors or thermocouple devices (PID or TCD detectors) in combination with gas alarms based on point- and line detectors are frequently used methods to secure work today. Remote sensing with mobile LIDAR systems are used to monitor gas released from large areas such as gas processing plants and occasionally from volcanoes (Lohberger *et al.*, 2007; Svanberg, 2002). Point-detectors based on MEMS fabrication and thus miniaturization of the spectrometer could potentially complement existing point detectors (Lammel *et al.*, 2001). Optical gas imaging with UV (Bluth *et al.*, 2007), infrared (Hirsch and Agassi, 2010), or laser (Powers et al., 2000; Stothard *et al.*, 2000; Gibson et al., 2006) assisted cameras helps the operator to cover a wider area and find leaks undetected by point- or line-monitoring. The Environmental Protection Agency in the US recently allowed optical gas imaging as an alternative work practice for regulatory gas detection. Much effort is

**Corresponding Author Email: godsdayusiabulu@gmail.com*

now invested in taking the optical gas imaging from detection and quantification to flow rate estimation. Gas detection work is nowadays easily performed with handheld infrared cameras such as the gas absorption band optimized cameras from FLIR Systems. Gas imaging in combination with a spectrometer combines the direct camera view with specific concentration × path length values of the gas in each pixel. Infrared Fourier transform cameras are available from TELOPS and can be used to detect, image and quantify several gases. Remote methane gas-correlation sensing of e.g. pipelines from airborn platforms are performed by the company Synodon. The virtue of the imaging gas-correlation technique is the holistic discrimination between spectral frequencies with specific gas absorption and transparent areas, which is obtained by comparing a direct image to an image through an optically thick gas absorption cell (Sandsten *et al.,* 2000). Varying thermal background, reflectance or remittances over the image are compensated when using the gas-correlation technique. Real time gas images produced at frame rates above 18 Hz, makes it possible for human eye perception to follow the optical flow back and pinpoint the gas leak without having to wait for post-processing of the images. The gas process operators' situational awareness can thus be improved (Sandsten *et al.,* 2004). Therefore, the objective of this research is to estimate the gas leak volume to quantify gaseous fluid flow in processing plants using prior-calibration-relation techniques

MATERIALS AND METHODS

The methodology that was followed during this study includes important steps to building a Machine learning model. The first step is to collect the required dataset and a pre-processing phase which includes cleaning the data, attempting a linear regression model and other regressions (Random Forest). The linear regression model and the random forest were used for predicting tolerance and gas leak detection.

The second step is to train the proposed model and evaluate its performance. A detailed description of the methodology is summarized in Fig: 1

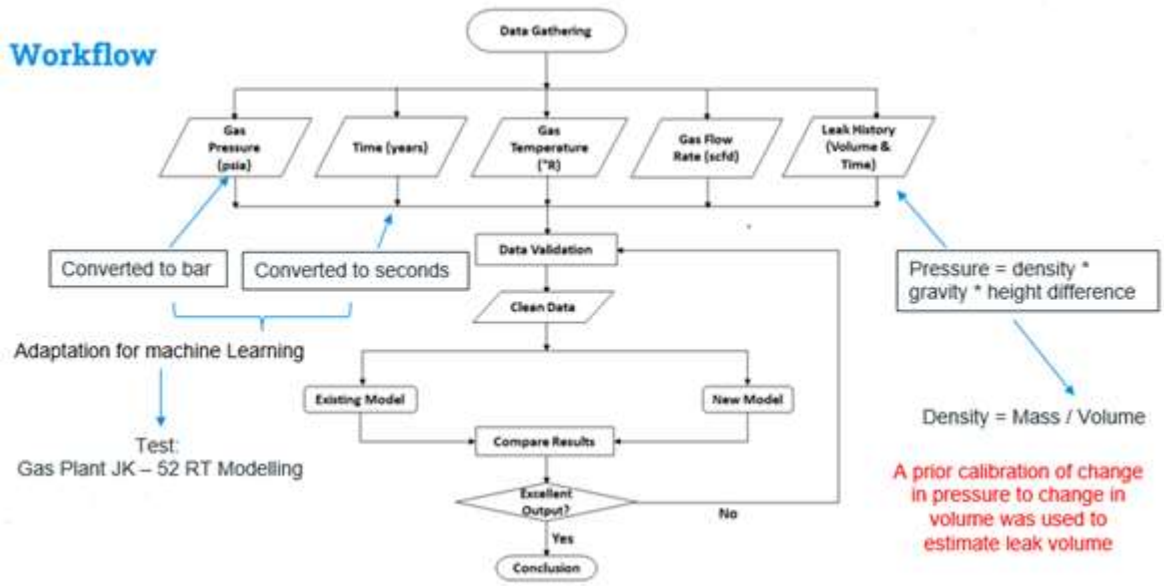

Fig 1: Detailed description

Reclassification of the Leakage Rate Calculation Models: Leakage rate calculation models are often classified into three types according to the conventional classification. This paper reclassifies them into four categories based on the real circumstances and provides the appropriate breadth of each model. Figure 2 (Montiel *et al.*, 1998) depicts the examined system conceptually. According to this diagram, there is a length of pipeline Le followed by a hole of a specific dimension through which the pressure is released. Point 1, at the pipe's commencement Point 2, in the pipeline's middle, on the same vertical axis as the leak point Point 3, at the leak point Point 4, at the pipe's exterior, exposed to atmospheric pressure, are all locations of importance.

The leakage rate is calculated using the following hypothesis (a) a model of essentially one-dimensional flow; (b) isentropic flow at the release point and adiabatic flow in the pipe; and (c) the gas behaves as an ideal gas. To make the ideal gas equation of state closer to the real gas, an air compression factor is included. The following equation is discovered by applying the energy and momentum equations to the adiabatic flow via a pipeline (Wojciech and Janusz, 2012):

$$\frac{k+1}{k} ln\left(\frac{P_1T_2}{P_2T_1}\right) + \frac{M}{RG^2}\left(\frac{P_2^2}{T_2} - \frac{P_1^2}{T_1}\right) + \left(\frac{4\lambda\chi_e}{D}\right) = 0 \qquad (1)$$

In this expression, λ is the Fanning friction factor. The natural gas leakage rate K at the hole can be calculated using the following expression, which is obtained from the continuity equation and the law of ideal gases for an isentropic expansion:

$$K = C_D A_{ot} P_2 \sqrt{\frac{M}{ZRT_2} \frac{2k}{k-1} \left[\left(\frac{P_a}{P_2} \right)^{2/k} + \left(\frac{P_a}{P_2} \right)^{k+1/k} \right]} \qquad (2)$$

Where C_D is the leakage hole's flow correction coefficient (Bariha et al., 2016), which is typically adjusted to a value between 0.6 and 1.0. The type of this coefficient depends on the design of the hole. It is typically advised to choose a conservative value of 1.0 when the precise geometry of the hole is uncertain. In this paper, this value was utilized. The critical pressure ratio (CPR) can be used to assess whether the flow is subsonic or sonic, which affects the flow rate at the leak point (Montiel et al., 1998):

$$CPR = \frac{P_a}{P_{2c}} = \left(\frac{2}{k+1} \right)^{k/k-1} \qquad (3)$$

Where P_{2c} is the critical pressure at point 2. If the pressure P_2 at point 2 increases gradually, the speed of gas leakage will increase until it is equal to the local sound speed. At this moment, if P_2 continues to increase, then the gas leakage rate remains constant and is always equal to the local sound speed and demarcates a critical stage of flow. When $P_a/P_2 < CPR$, then critical flow leakage has been reached and equation (4) substituted into equation (2) for the expression of the leakage.

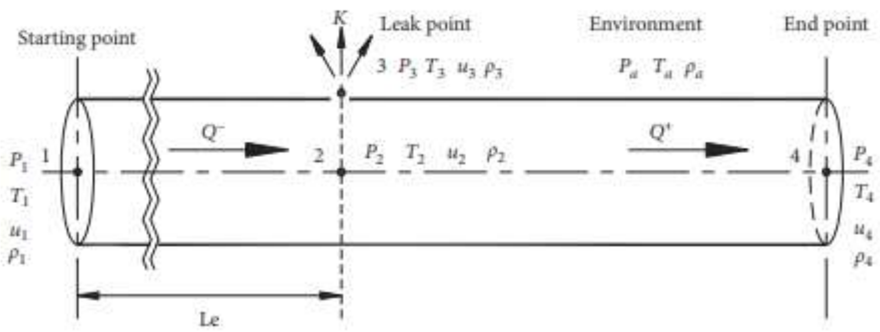

Fig 2: Schematic diagram of a gas pipe leakage

$$K = C_D A_{ot} P_2 \sqrt{\frac{Mk}{ZRT_2} \left[\left(\frac{2k}{k+1} \right)^{k+1/k-1} \right]} \qquad (4)$$

When $P_a/P_2 \geq CPR$, the leakage is at subcritical flow, and the leakage can be calculated by equation (2). Equations (2) and (4) are general formulas for calculating the natural gas leakage rate.

According to different but approximate conditions, natural gas pipeline leakage models (i.e., storage tank model, small hole model, modified hole-pipe model, and pipe model) are established in this paper.

Storage Tank Model: When a gas storage tank leaks, the following approximate assumptions can be made because of the large size of the tank: (a) The pressure inside the storage tank is not affected by the leakage, and the parameter values at point 2 remain unchanged both before and after the leakage. (b) The pressure loss caused by the friction between the container and the gas flow after the leakage is ignored. By these two assumptions, the parameters of point 1 are used to replace the parameter value of point 2, and the leakage rate can be calculated by formulas (2) and (4), which comprise the storage tank model. This model has been widely used in the accurate calculation of the leakage of large containers, such as storage tanks (Arnaldos et al., 1998). All these aspects make this model adequate for the prediction of release through a hole in a tank but not for leakages in natural gas pipelines. Because the gas pipeline is different from the storage tank, especially when point 2 is far from point 1, the pressure loss and velocity caused by internal friction must be considered. The related parameters of point 2 are not exactly the same as those at point 1. The leakage rate calculated by this model is larger than the actual leakage rate. Therefore, in general, the storage tank model is not suitable for the calculation of the natural gas pipeline leakage rates. Only when point 2 is close to point 1 and the hole diameter is very small can the storage tank model be used to calculate the leakage rate for natural gas pipelines.

Small Hole Model: A small hole model is used to calculate the natural gas pipeline leakage rate when the hole is small. This model takes into account the effect of friction in the natural gas pipeline. Because the leakage is small, the effect of leakage on the pressure and flow rate in the natural gas pipeline is neglected. Assuming that the coefficient of friction is the same along the whole pipeline, the relationship between point 1 and point 2 can be defined by the following equations (Montiel et al., 1998)

$$\frac{k+1}{2} ln\left[\frac{Ma_2^2}{Ma_1^2}\frac{2+(k-1)Ma_1^2}{2+(k-1)Ma_2^2}\right]-\left(\frac{1}{Ma_1^2}-\frac{1}{Ma_2^2}\right)+\frac{4\lambda X_c}{D}=0 \quad (5)$$

$$\frac{T_2}{T_1}=\frac{Y_1}{Y_2} \quad (6)$$

$$\frac{P_2}{P_1}=\frac{Ma_1}{Ma_2}\sqrt{\frac{Y_1}{Y_2}} \quad (7)$$

$$\frac{\rho_2}{\rho_1}=\frac{Ma_1}{Ma_2}\sqrt{\frac{Y_2}{Y_1}} \quad (8)$$

Where

$$Y_i = 1+\left(\frac{k-1}{2}\right).Ma_i^2 \quad (9)$$

In these expressions, Ma is the Mach number, which can be calculated as presented in equation 10

$$Ma_i=\frac{u_i}{c}=\frac{u_i}{\sqrt{kZRT/M}} \quad (10)$$

Under these conditions, the following relationships apply: When $P_a/P_2 < CPR$, there is a critical flow at the leak point, and the leakage rate can be calculated by equation (4). When $P_a/P_2 \geq CPR$, there is a subcritical flow at the leak point, and the leakage rate can be calculated by equation (2). The small hole model considers the pressure loss caused by the friction of the natural gas pipeline and is more accurate than the storage tank model. However, because the small hole model neglects the effect of leakage on the pressure and flow rate in a natural gas pipeline, the parameters at point 2 remain unchanged upstream and downstream of the leakage. This hypothesis is still different from the actual situation. Therefore, only when the leakage hole is very small can the small hole model be used to calculate the leakage rate.

Pipe Model: The pipe model is used for the case of the complete rupture of the natural gas pipeline or when the leakage diameter is close to the pipe diameter. The state of the natural gas in the pipe is the same as if the gas is in atmospheric conditions. According to the conservation of flow rate, the leakage rate is equal to the flow rate in a natural gas pipeline. Thus, the formula for calculating the natural gas leakage rate is as follows (Arnaldos et al., 1998):

$$K=Q=C_D A_{ot}\sqrt{\frac{2M}{ZR}*\frac{k}{k-1}*\frac{T_2-T_1}{(T_1/P_1)^2-(T_2/P_2)^2}} \quad (11)$$

At this time, because the pipeline is completely broken, $P_2 = P_3 = P_a$, and T2 can be obtained by using equation (6). The model gives good predictions for the case of the complete destruction of the natural gas pipelines, but it cannot be applied to the flow through holes with a diameter smaller than the natural gas pipeline diameter.

Modified Hole-Pipe Model: Before introducing the modified hole-pipe model, the hole-pipe model should be introduced first. Two aspects have been taken into account by the hole-pipe model: the pressure loss caused by the friction of the pipeline and the effect of leakage on the pressure in the pipeline. However, the effect of the leakage on the flow rate upstream of the leak point is not considered. In the hole-pipe model, the leakage rate is also calculated by equations (2) and (4). Equations (5)–(10) express the relationship of parameters between points 1 and 2, and these equations are substituted into equations (2) and (4) to reflect the consideration of pressure loss caused by the friction of the natural gas pipeline. For the critical flow at the leak point hole, the relationship of parameters between points 2 and 3 is defined as follows:

$$\begin{cases} P_3=\left[\frac{2}{(k+1)}\right]^{k/(k-1)}P_2, \\ T_3=\left[\frac{2}{(k+1)}\right]T_2, \\ \rho_3=\left[\frac{2}{(k+1)}\right]^{1/(k-1)}\rho_2. \end{cases} \quad (12)$$

For the subcritical flow at the leak point hole, the pressures at point 3 and the environment are same, so the relationship of parameters between points 2 and 3 is defined as follows:

$$\begin{cases} P_3=P_a, \\ T_3=\left(\frac{P_a}{P_2}\right)^{(k-1)/k}T_2, \\ \rho_3=\left(\frac{P_a}{P_2}\right)^{1/k}\rho_2. \end{cases} \quad (13)$$

Equations (12) and (13) are used to calculate P_2 after leakage occurs, and this can reflect the effect of leakage on the pressure, but the calculations are complicated. The above is the main introduction of the hole-pipe model.

More mathematical insight: In a research work carried out by (Mutiu et al 2019), it was concluded that the leak flow through the crack (pipe) in mass (oil) was quantified using the following equation:

$$Q = \alpha A \varphi_{max} \sqrt{2} P_{\rho} \quad (14)$$

Where A is the cross-sectional area of the crack in m2, α represents an area correction factor, ρ represents the gas density function in kg/m3, P is the absolute pressure in Pa and φ_{max} is the maximum leak rate and is computed to be 0.4692.

And the flow dispersion function φ_{max} for CO_2 gas from the pressurized enclosure was computed with the equation below (Mutiu Adesina *et al*, 2019):

$$\varphi_{max} = \left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)} \sqrt{\frac{\gamma}{\gamma+1}} \quad (15)$$

Where γ represents the specific heat ratio of CO_2. And the CO_2 gas density is adopted from the ideal gas law and is presented as (Mutiu Adesina *et al*, 2019):

$$\rho = \frac{P}{R_{CO_2} T} \quad (16)$$

Where R_{CO_2} represent specific gas constant of CO_2 (= 188.9 J/kgK) and T represents flow temperature in degrees Kelvin.

The study employed an experimental flow rig with a certain internal diameter of 50 mm and the volumetric rate of the leakage was determined using numerical computation above (eq 01), without considering some physical parameters affecting the pipelines including the thickness of the pipe used (and other parameters). This can alone, produce the wrong results when it is not inputted.

Sajjad (2022) in his research paper titled, "A Method for Pipeline Leak Detection Based on Acoustic Imaging and Deep Learning" used An Autoencoder Background Method. An Autoencoder consists of three layers: the input, hidden, and output layers. Together, the input and hidden layers form the encoder, while the same hidden layer combines with the output layer to make the decoder part of the autoencoder. The main purpose of the encoder network is to learn the hidden representation from the input data, whereas the decoder uses these representations to reconstruct the input data. The encoder part of the autoencoder was formalized using the equation:

$$h = a(w_1 x + b_1) \quad (17)$$

A minimum of about three regression equations should be gotten and compared, to pick out the average/most suitable equation best fit for the research.

Leak Index: Leak Detection is done by residual analysis. The intelligent model as used by Oluwatoyin Akinsete and Adebayo Oshingbesan (2019) in their research work for Leak Detection in Natural Gas Pipelines acts as an observer for the pipeline. It predicts the outlet flow rate using basic operational parameters only. A leak detection algorithm works in tandem with the intelligent model to detect a leak when a leak index is greater than a particular threshold. To avoid false alarms, the leak alarm is set to be persistent for three or more input data before an alarm is issued. The flow rate residuals are monitored for the previous one hour and the number of residuals (a) greater than a particular threshold is counted and used to derive a leak index. The leak index formula is in an exponential form. It is basically a modified form of the sigmoid function used in logistic regression and neural network models. It is given as:

$$f(a) = \frac{1}{1+ exp^{-a}} \text{ (Sigmoid function)} \quad (18)$$

$$f(a) = exp\left(\frac{-1}{1+ a^2}\right) \text{(Modified function)} \quad (19)$$

The modified function (eq 6) was chosen as the leak index function because it makes the model to be more robust to false alarms. But no, the sigmoid function has its own role to play in leak detection. The Modified function is prone to introduce undesirable zigzagging dynamics in the gradient updates for the weights when the graphs are drawn according to the formulas stated above (eq 05 & 06).

Dynamic modelling of the system: According to Pablo *et al* (2018) in their published work on Leak Detection System Using Machine Learning Techniques, the development of the leak detection system begins with the working fluid dynamics behavior modelling, using existing instrumentation. Mathematical modeling of the system was made based on the energy conservation principle. For this, the pipe was simplified to a model close to that of Figure 3: In figure 3 and equation 20, where: Pa, Pb: the pressure measurement points; ρ= average fluid density; Za, Zb = relative height of the points "a" and "b"; va, vb = flow velocity of the fluid at points "a" and "b" respectively.

This is for a perfect situation of pipe lying horizontally or vertically 0/90 degrees. It failed to consider pipes lying across angles, inclined planes. These cases are special ones, in which in reality, they need to be considered.

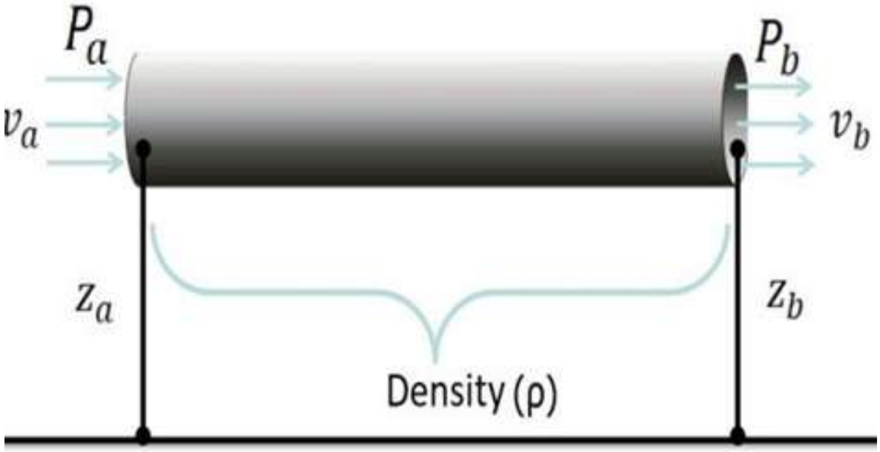

Fig 3: Pipeline simplification

$$\frac{\text{Pa}}{\text{Pg}} + Z_a + \frac{V_a^2}{2g} = \frac{\text{Pb}}{\text{Pg}} + Z_b + \frac{V_b^2}{2g} + h_f \qquad (20)$$

Mass (or Volume) Balance Methods: The Mass (or Volume) Balance Method used in the research paper "Leak Detection in Pipeline Systems and Networks: A Review" (Xiao-Jian Wang *et al,* 2001). Mass (or volume) balance leak detection methods follow the principle that the metered inlet volume, less the metered outlet volume, less the change in mass inventory (or line pack) due to the compressibility of the fluid and pipes should always be zero if the pipeline is not leaking, this is;

$$V_L = V_{in} - V_{out} - \Delta V \qquad (21)$$

Where V_L = leakage volume; V_{in} = metered inlet flow; V_{out} = metered outlet flow and ΔV = pipeline pack or inventory.

This method and the pressure-flow deviation method are the most used model-based leak detection programs in the oil and gas industries (Griebenow and Mears 1989; Furness and Reet 1998). I suggest the combination of both methods to give a very good Leak Detection, since the use of one method doesn't interfere with the other.

A Test Case For Gas Plant JK - 52 Real-Time Modelling: The estimation of gas volume loss when a gas cylinder is depressurized can be achieved by normalising the pressure reading in the gauge at the regulator. The change in pressure in the gauge` may be calibrated against the change in weight or change in volume of the gas cylinder. Thereby, the indication quantifies loss/leak/utilization and eventual depletion of the gas cylinder.

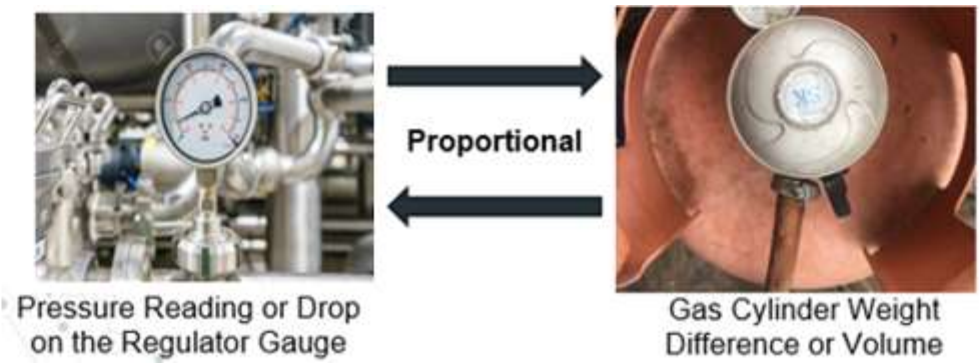

Fig 4: Illustration using cooking gas

Example / Illustration

Consider a 13kg gas cylinder of X Volume, which the gauge reads Y Psi when full.

When the pressure on the gauge reads $\frac{Y}{2}$, then the volume change is $\frac{X}{2}$.

The volume change or losses due to leakage could always be estimated from the change in gauge pressure. Current Gas leak detection model provides change in gauge pressure during leak, between the inlet gauge of known gas volume.

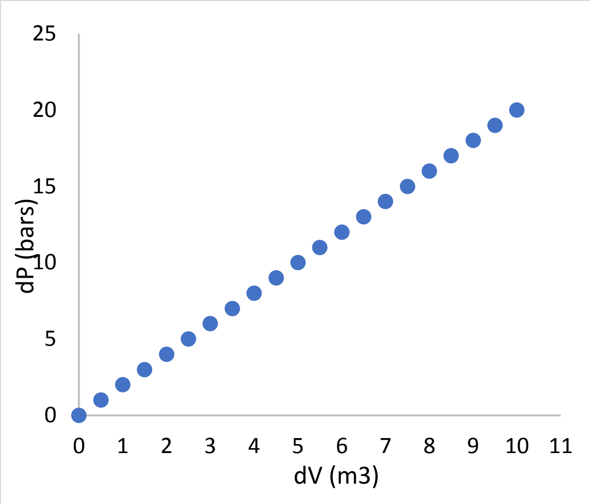

Fig 5: Pressure drop versus gas leak volume

Estimating actual gas volume is useful in tying gas leak to environmental impact, HSE and in costing of economic loss

Leak Volume = **2.40 m^3** or **84.7 scf of gas**

As a result of leaks, the pressure drops. Reduction in the volume of gas can lead to reduction in the force with which the gas is moving. This will in turn lead to a drop in pressure. From the analogy above in fig 5, pressure dropped by 5 bar.

Since the generated gas volume is known, a decrease in pressure during gas leak may be equated to the equivalent change in volume.

With "normalization" process, the change in pressure dP may be plotted against the change in volume dV in a prior calibration to derive a relationship between dP and dV, as shown below.

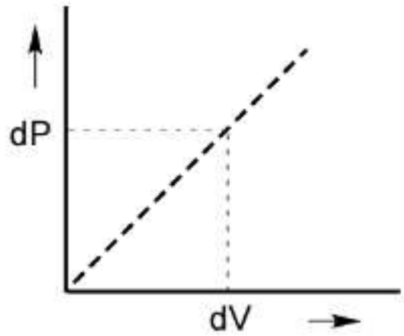

Fig 6: Pressure versus Volume Relation

Where δV is the leaked Volume of gas for the change in Pressure δV

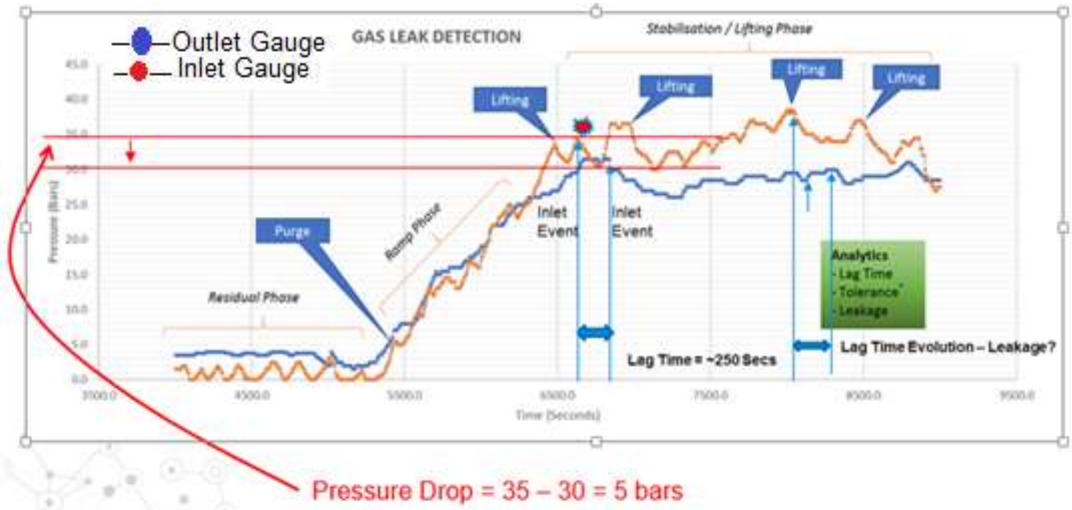

Fig 7: A Priori-calibration-relation for Gas Plant JK – 52 Case Leak

Fig 7 shows the pressure drop as a result of leakage. The pressure drop is calculated as 5 bars. In addition to wasting a source of energy, leaked natural gas mostly methane is a powerful greenhouse gas. It is a significant contributor to climate change that makes it essential for gas utilities, and the regulators and public officials that oversee them, to act swiftly and decisively to repair and prevent all methane leaks. The gas utilities' pipe systems are just one link in the national gas supply chain that brings gas from the well to your home. Leaks are an issue at every stage, starting at the wellhead. That's why we're addressing leaks throughout the system (Kedarpotdar et al., 2013). Most leaks don't pose an immediate threat to safety, but some can (Zukang, et al., 2021). We have shared the maps and leak indicators with local gas companies. If you ever smell gas, or have any reason to suspect a problem, experts say to immediately exit the building or area. Don't light matches or smoke, and don't use any electrical devices including a phone until you are away from the suspected leak then call your local utility. The major health concern about outdoor methane leak is that they contribute to smog which aggravates to asthma and other respiratory conditions.

(Zukang, et al., 2021). Gas leaks are invisible, unregulated and majority go unnoticed. These leaks may depend on any of the following: operation practices, equipment age and maintenance. Leaks and venting at natural gas processing plants release other pollutants (e.g., benzene, hexane, hydrogen sulfide) besides methane that can threaten air quality and public health. Hence, there is need for early detection of gas leaks by using appropriate Machine Learning models. Nigeria is a province of gas with pockets of oil (Teriba, 2018), and the use of pipeline is considered as a major means of conveying petroleum products which serves as the major assets to the Nigeria economy and should well protected.

Conclusion: In conclusion, *a* comparison and analysis of the calculation results in this paper shows that the calculation model can calculate the leakage rate at any leak point diameter. For Gas Plant JK – 52 Case, a drop in pressure shows that there is a leakage.

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