Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 10 Issue 3, March - 2023

Analytical Model Of Leak Detection And Location For Application In Oil Pipeline Intrusion Detection System

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***Abstract*— In this paper, analytical model of leak detection and location for application in oil pipeline intrusion detection system is presented. Specifically, modeling of oil pipeline intrusion system using linear differential flow analytical models for the cases of single leakage and multiple leakages are presented. The oil pipeline intrusion detection system is basically a microcontroller based device that uses two sensors located at two ends of an oil pipeline segment to monitor the oil flow pressure and based on the drop in pressure can apply the mathematical models presented in this paper to determine if leakage and hence intrusion has occurred on the pipeline. Notably, the model is based on the assumption that the fluid is homogenous, the flow can be laminar or turbulent and there isothermal flow condition. Proteus software is used to simulate the oil pipeline intrusion system operations by separately injecting single leaks and multiple leaks and monitoring the system's responses in detecting the leaks and their locations along the pipeline based on the analytical models developed in this paper. The results show that for the single leakage point, and where the leakage pointt is located 8 km from sensor 1, the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 varied from 1.8 at V= 50 m^3/s to 1.3 at V = 10 m^3/s. The results also show that the leakage is detected in all the 5 different values of V that were used in the simulation. Similarly, for the double leakage, the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 varied from 2.42 at V= 50 m^3/s to 2.00 at V = 10 m^3/s. Finally, for the triple leakage points, the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 varied from 1.9 at V= 50 m^3/s to 1.34 at V= 10 m^3/s. In all, the simulation results show that the mathematical model can effectively be used to detect the occurrence of single leakage and multiple leakages in a pipeline and it can also be used to estimate the location of the leakage point relative to the sensors.**

Keywords*— *Oil Pipeline, Linear Differential Flow, Pressure Differentials, Leakage Detection, Proteus Software, Flow Valve, GSM 900 Module

1. Introduction

In the present day Nigeria, oil product has being the mainstay of the economy [1,2]. Also, in the transportation of petroleum products, pipelines are crucial infrastructure used to carry these product from the production point to the various distribution points [3,4]. As such, protection of oil pipeline has become very necessary thus, the need to look for ways to improve on the security network around oil pipeline. In this paper, analytical model of leak detection and location for application in oil pipeline intrusion detection system is presented.

Basically, oil pipeline intrusion detection system is a microcontroller based device that uses two sensors located at two ends of an oil pipeline segment to monitor the oil flow pressure and based on the drop in pressure can apply the mathematical models presented in this paper to determine if leakage and hence intrusion has occurred on the pipeline [5,6]. In some intrusion detection systems, the sensor nodes are part of Internet of Thins (IoT) network. In that case, they rely of sensor network transceiver technology like the Longe Range (LoRa) to communicate to the gateway or base station and then to the Internet [7]. In such case also, the intrusion detection system design must account for the various signal attenuation mechanisms that are prevalent in wireless communication links. In addition, in a big setup, the intrusion detection sensors can be part of a cluster in an IoT or wireless sensor network in which case the sensor nodes transmits to the cluster heads from where there data is relayed to the gateway or base station and then to the internet [8]. However, in this paper, the approach adopted is the use of GSM network interface to connect the intrusion detection to the internet. Requisite mobile software application and microcontroller firmware are required to handle the interaction between the GSM end-user and the GSM handset and also between the GSM handset and the intrusion detection hardware device.

In any case, the major reason for employing intrusion system is to support the pipeline controllers in the detection and location of leaks along the oil pipeline [9,10]. The intrusion system also provides alarm and display mechanisms to enhance the oil pipeline intrusion detection and management. Particularly, through the GSM link, the pipeline controllers can be remotely notified of the leak status along the pipeline in real-time and he also has the opportunity to effect some control measures on the pipeline management system. Furthermore, the application of the intrusion system also help to reduce downtime as it helps to speed up leak detection and location.

Notably, the analytical model presented in this paper is based on the assumption that the fluid is homogenous, the flow can be laminar or turbulent and there isothermal flow condition. Proteus software is used to simulate the oil pipeline intrusion system operations by separately injecting single leaks and multiple leaks and monitoring the system's responses in detecting the leaks and their locations along the pipeline based on the analytical model presented in this paper. The details of the mathematical model and simulations using Proteus software are presented along with the discussion of the simulation results.

2. Methodology

The focus of this paper is to develop model for oil pipeline intrusion system [11,12,13] using linear differential flow equations [14,15,16]. Then, the Proteus software [17,18,19,20] is used to simulate the oil pipeline intrusion system operations and injecting single leaks and multiple leaks and monitoring the system response in detecting the leaks and their locations along the pipeline based on the analytical models developed in this paper.

The operation of the oil pipeline intrusion system is based on the flow diagram of Figure 1. It is basically a microcontroller based device that uses two sensors located at two ends of an oil pipeline segment to monitor the oil flow pressure and based on the drop in pressure can apply the mathematical models presented in this paper to determine if leakage and hence intrusion has occurred on the pipeline ;21,22,23,24,25]. When intrusion is detected, the system can use its GSM interface to place a call automatically to the control engineer who will respond accordingly to send appropriate command to the system to close the flow valves. Also, if the system is set to respond in auto mode, then the system will send appropriate command to the system to close the flow valves without going through the control engineer. The actual process of detecting single leak or multiple leaks along the pipeline segment is based on linear differential flow analytical models which are present in the section that follows [26,27,28]. The models effectiveness is evaluated through the model simulation that is conducted using Proteus software.

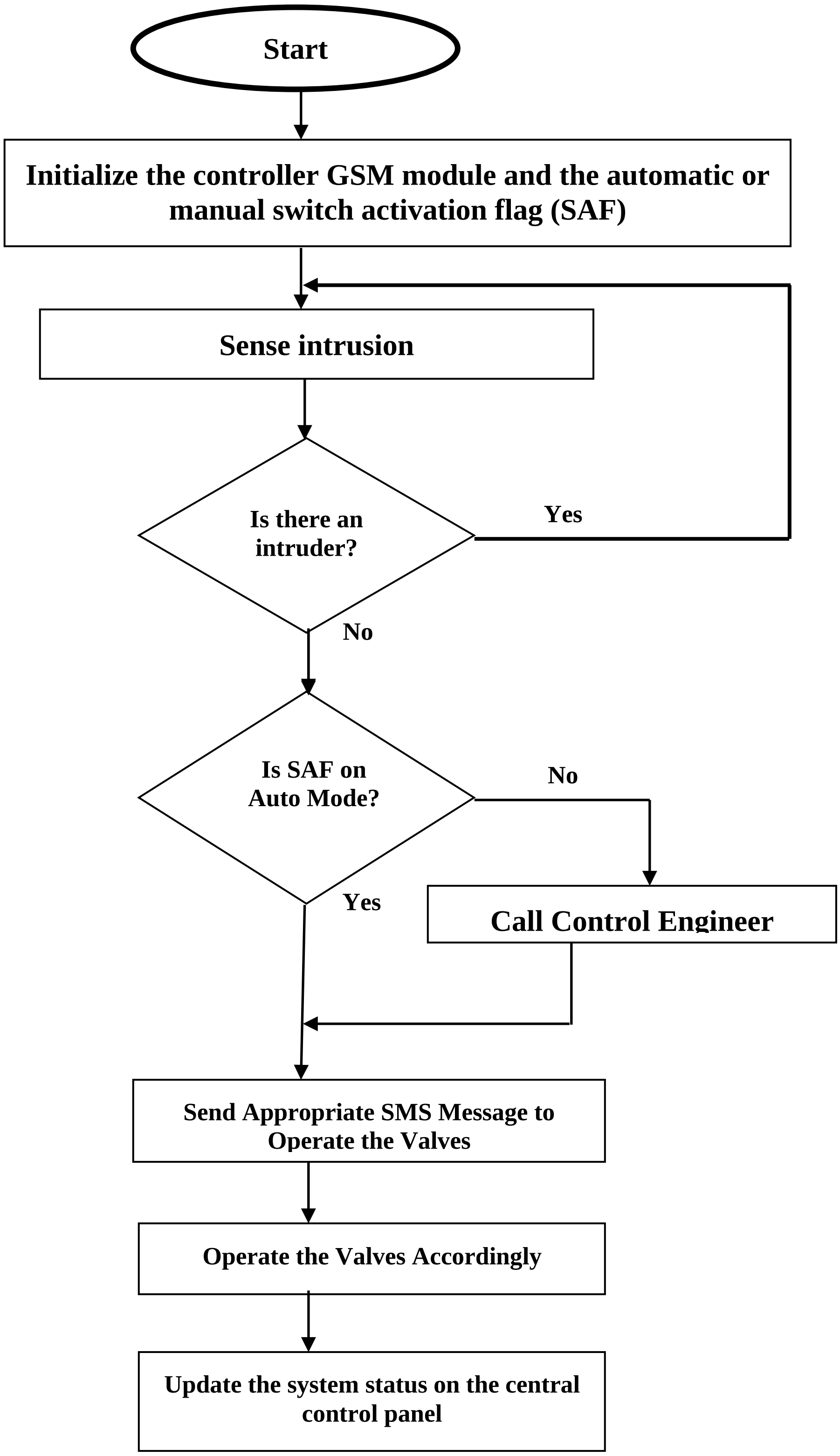

Figure 1 The operation of the oil pipeline intrusion system

2.1 Mathematical model for the flow in a pipeline with a single point of leakage

The analysis presents the flow model of a pipeline with a single point of leakage and another case with more than one leakage. The diagram in Figure 2 shows a flow model of a pipeline with a single point of leakage, and the associated model parameters are such that one segment of the pipeline is considered and there exist a single leak on the pipeline. Also, the model is based on the assumption that the flow can be laminar or turbulent and there is isothermal flow condition. Finally, it is assumed that the fluid is homogenous. The model in Figure 2 shows that two sensors 1 and 2 are used in estimating the location of the leakage. Specifically, the location of the unknown single point of leakage which occurs along the pipeline is estimated using mathematical models that are based on the time of sensing between the two sensors referred to as sensor 1 and sensor 2, as shown in Figure 2, where a_{x1} denotes the propagation velocity of pressure wave between sensor 1 and leak point Li and it is expressed in m^3/s; a_{x2} denotes the propagation velocity of pressure wave between sensor 2 and leak point Li and it is expressed in m^3/s; L-X denotes the distance from leak point to the pressure sensor 2 and it is expressed in m; X denotes the distance from sensor 1 to leak point Li and it is expressed in m and V denotes the original velocity of flow from sensor 1 to sensor 2 and it is expressed in m^3/s.

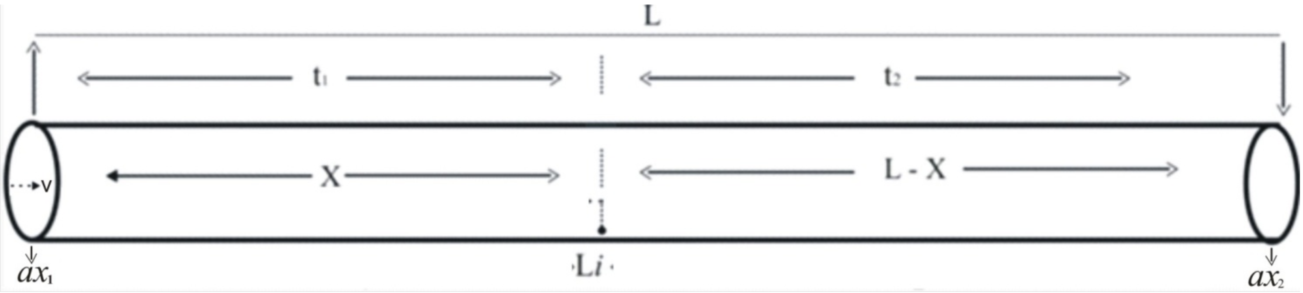

Figure 2 The flow model for a single leakage point along the pipeline

In order to determine the inflow pressure before the occurrence of intrusion point the following analytical expressions apply;

$$t_1 - t_o = \int_o^x \frac{1}{a_{x1} - V} dx = \frac{X}{a_{x1} - V} \quad (1)$$

$$t_2 - t_o = \int_X^L \frac{1}{a_{x2} + V} dx = \frac{L - X}{a_{x2} + V} \quad (2)$$

where X(m) denotes the distance from intrusion or leak position to the sensor 1, L(m) denotes the distance between sensor 1 and sensor 2, Li denotes the point where the leak occurred and V(m/s) denotes the propagation velocity of the fluid pressure wave within the pipeline.

Let Δt denote the difference in time for the wave to travel from sensor 1 to the end of sensor 2, where;

$$\Delta t = t_1 - t_2 \quad (3)$$

Then,

$$\Delta t = \frac{X}{a_{x1} - V} - \frac{L - X}{a_{x2} + V} \quad (4)$$

According to a study by Wang S. and CarrolJ.J (2006), if there is a change in elasticity of fluid pressure, the fluid velocity will change accordingly, hence, the pressure wave is estimated using the expression;

$$a = \sqrt[2]{\left(\frac{K/_P}{1+(K/_E)(\frac{D}{e})C}\right)} \quad (5)$$

where P (kg/m^3) denotes the liquid density, K (Pa) denotes the liquid bulk modulus of elasticity, E (Pa) denotes the modulus elasticity, C denotes the correction factor related to the pipeline constraint and e (m) denotes the pipeline thickness.

2.2 Mathematical model for the flow in a pipeline with one leakage and with more than one point of leakage

The diagram in Figure 3 shows a flow model of a pipeline with more than a single point of leakage and the associated parameters as stipulated by Mutiu A.A et al (2019) include H which denotes the pressure head length expressed in m, Q which denotes the flow velocity expressed in m^3/s , L which denotes the length of the pipe expressed in m , T which denotes the time of flow expressed in s , Q which denotes the Acceleration due the gravity expressed in m^2/s , D which denotes the pipeline diameter expressed in m and V which denotes the speed expressed in m/s.

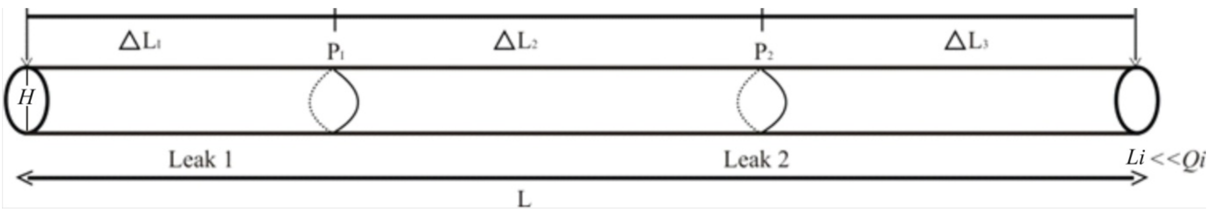

Figure 3 Distributed model of a pipeline with more than one leakage point

For the dynamic equation pertaining to the fluid flow along the pipeline, the study considered the model presented by Li, Q. et al, (2018) which is expressed as follows:

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial L} = 0 \quad (6)$$

$$\frac{\partial Q}{\partial L} + gA\frac{\partial H}{\partial t} \quad (7)$$

When a leakage occurs there will be a corresponding, discontinuity at point L_i where i = 1, 2 …… n, hence,

$$Q/L_i = \sqrt{H/L_i} \quad (8)$$

Therefore, for a pipeline with n-1 leakages there exist “n” pairs of the Equation 6 with differential flow conditions that exists between each section of the pipe, where the differential flow conditions is expressed as follows:

$$Qb/Li = Qa/L_i \quad (9)$$

Where Qa/L_i and Qb/L_i denote are the previous and the later leakages. Now when the length of the pipeline is specified and assuming that the leakage is at a single point, then,

$$\Delta L = Li/n \quad (10)$$

Estimated partial derivative from pressures and the flow is in variation as shown below,

Also, the partial derivative estimated from pressures and the fluid flow are in variation which are expressed as follows;

$$\frac{\partial H}{\partial L} \cong \frac{\mathrm{H}_{\mathrm{i+1}} - \mathrm{H}_{\mathrm{i}}}{\Delta \mathrm{L}} \qquad (11)$$

$$\frac{\partial Q}{\partial L} \cong \frac{Q_i - Q_{I-1}}{\Delta \mathrm{L}} \qquad (12)$$

Where the index *i* denotes the variation along the pipeline and the marginal condition for every section of the pipeline is expressed as;

$$\mathrm{Qi} = \sqrt{Hi} \qquad (13)$$

Further simplification gives;

$$\frac{\partial Qi}{\partial t} = a_1(Hi - Hi_{+1}) \qquad (14)$$

$$\frac{\partial Hi}{\partial t} = a_2(Qi - Qi_{-1}) \qquad (15)$$

Where

$$\mathrm{a}_1 = g\pi_r 2n/_{\mathrm{L}}\ with\ n = 1 \qquad (16)$$

$$a_2 = \frac{b_2 \mathrm{L}}{g\pi r 2n}\quad with\ n = 1 \qquad (17)$$

In the situations where there are several leakages unequally distributed ΔL is variable and values of the parameters a_1 and a_2 are having equal pressures at both the inlet and the outlet associated with the gap between the leakage points. In such situation, H_1 and H_3 represents the pressure heads of the pipeline while Q1 and Q_2 represents the measured flows all over the pipeline.

3. System Simulation, Results and Discussion

3.1 Simulation of the system in Proteus Software

The testing and simulation of the model work was done using Proteus virtual system modeling software. The Proteus 8.4 simulation software contained most of the components required for the simulation of the electrical components or their equivalent components. During the simulation, a continuous flow of fluid was indicated by the flow sensors. A drop in flow pressure is identified by interaction of sensors 1 and 2 in the flow terminals which is recognized in the Arduino board as detectable change in the state of the system hence, sending a call signal to the GSM. This is implemented in the circuit presented in Figure 4 for the flow measurement terminal 1.

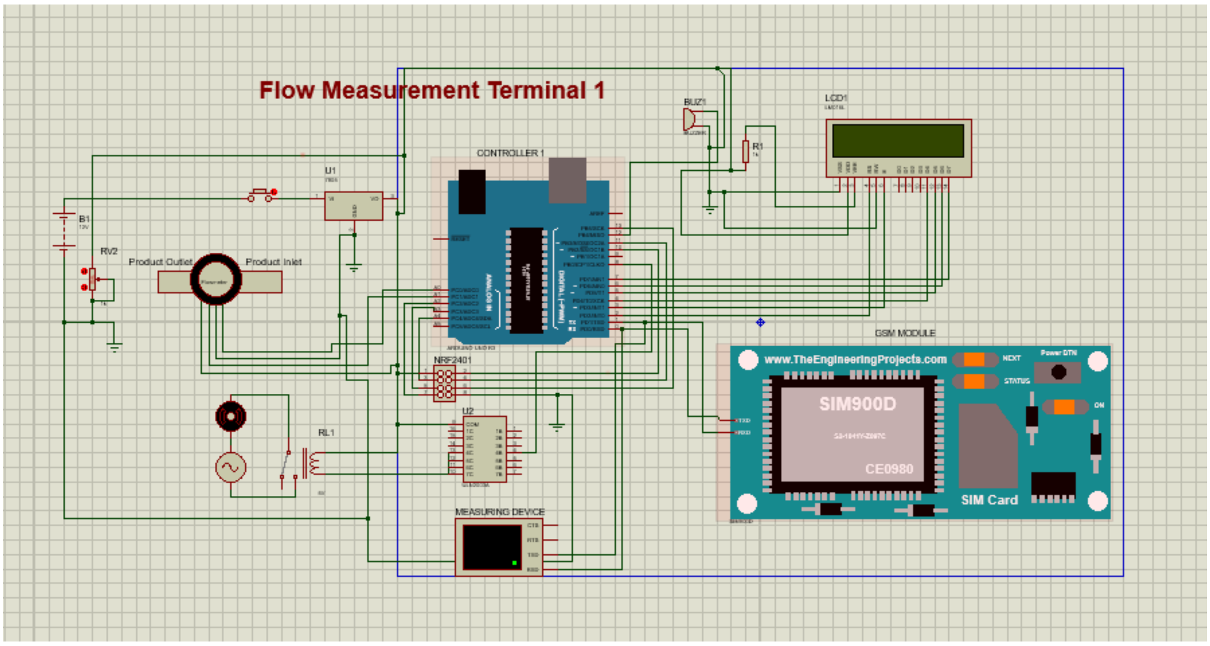

Figure 4 The circuit diagram of the flow measurement terminal 1

The circuit is a transceiver circuit configured to pick up the inflow pressure using a virtual flow measurement device. This flow measuring device takes the value of inflow pressure and compares it with the outflow pressure using the NRF 2401 which acts as a comparator that compares by interacting with the two terminals. The signal obtained is recorded on the LCD while the simulation of the system triggered the buzzer when a set threshold of pressure was attained by the outflow sensor. This implies the presence of a leakage along the pipeline. The circuit diagram of the flow measurement terminal 2 is presented in Figure 5.

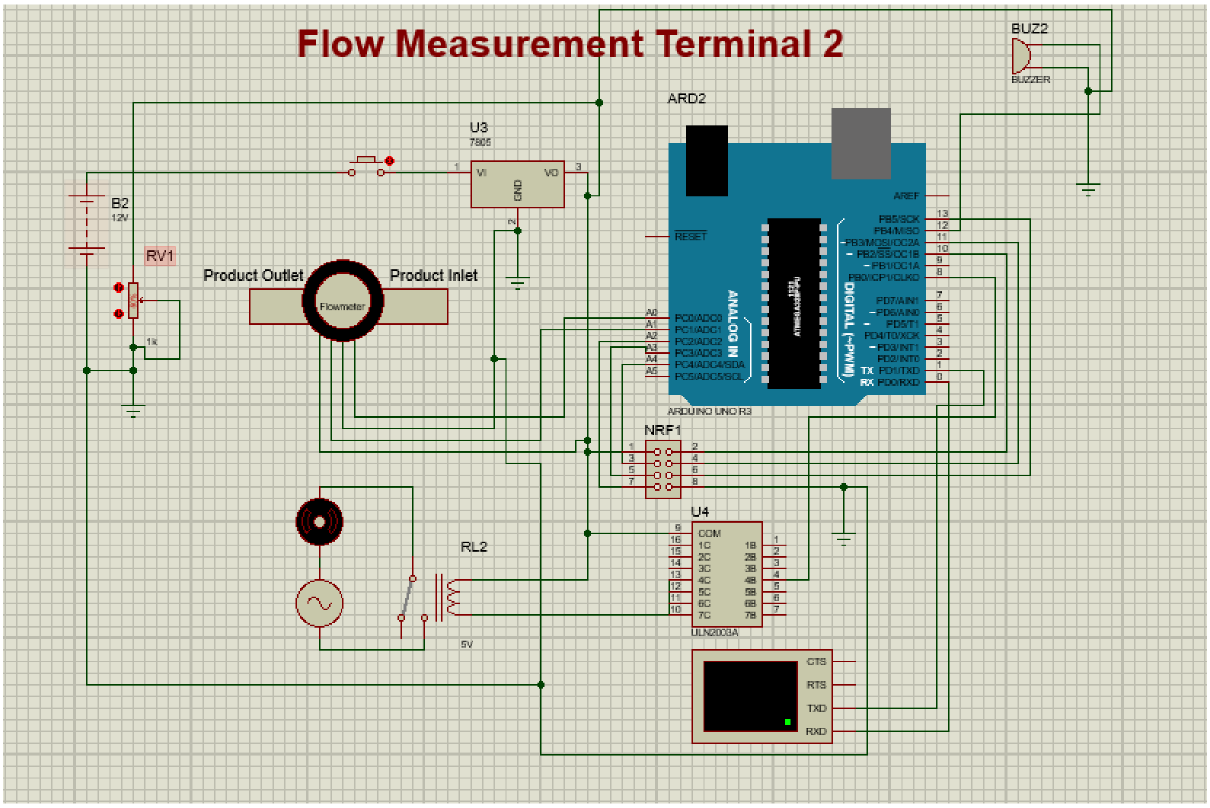

Figure 5 The circuit diagram of the flow measurement terminal 2

For the flow measurement terminal 2, it takes record of the outflow pressure of the oil flowing through the pipeline. It is similar to the flow measurement terminal 1, but differs in the sense that terminal 2 takes record of the outflow characteristics of the oil and presents same on the LCD.

During simulation, a differential of the record of sensor 1 and sensor 2 activates the buzzer which in real life, is a transmission signal sent across to the GSM module which alerts the control personnel. When intrusion is noticed, the control engineer sends an SMS command of “close valve” to the GSM configuration which serves as a switch to the solenoid valve. This is represented as a switch connected to the pump in the simulation. The close valve command shuts down the pump on activation of the GSM module attached to it by the SMS from the control engineer thereby stopping the flow of oil along the pipeline.

A motor which represents the pump was employed for the purpose of pumping the fluid along the pipeline at a predetermined speed assumed to be the pressure of flow. The flow sensor used in the design notices a drop in flow pressure as a drop in electrical flux which implies intrusion; the control unit for the outflow sensor sends out signal to the Arduino target board which is picked up by the GSM module and sent as a call signal from the GSM module to the GSM operator/control personnel.

The system resets after transmitting the call signal to the control engineer. The solenoid valve which is electronically controlled is represented using a switch in the Proteus software package. On receiving a call from the flow sensors GSM configuration, the engineer/control personnel sends an SMS to the GSM module embedded in the control unit of the solenoid valve (in this case, a switch), the switch is locked, shutting down the motor. This implies a ceasure in the flow of oil along the pipeline.

3.2 Result for the Mathematical Model

The results of the simulation showing the time different at which the outflow sensor sensed an intrusion as determined using the mathematical model with respect to varying flow velocities at sensors 1 and 2 are shown in Table 1 to Table 6.

3.2.1 The Results for Single Leakage

The results for single leakage for separation distance of 20 km from between sensor 1 and sensor 2 and where the leakage point is located 10 km from sensor 1 are shown in Table 1 and Figure 6 where the original velocity , V(m3/s) of flow from sensor 1 to sensor 2 is varied from 50 m3/s to 10 m3/s. The results show the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 varied from 1.8 at V= 50 m3/s to 1.3 at v= 10 m3/s. The results also show that the leakage is detected in all the 5 different values of V that were used in the simulation.

Similarly, the results for single leakage for separation distance of 20 km from between sensor 1 and sensor 2 and where the leakage point is located 8 km from sensor 1 are shown in Table 1 and Figure 6 where the original velocity , **V**(m^3/s) of flow from sensor 1 to sensor 2 is varied from 50 m^3/s to 10 m^3/s. The results show the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 varied from 1.47 at V= 50 m3/s to 0.8 at v= 10 m^3/s.

As seen in Figure 6, the value of $\Delta t_{(Min)}$ increases with **V.**

Table 1 The results for single leakage for separation distance 20 km between sensor 1 and sensor 2 and the leakage point is 10 km from sensor 1

The original velocity of flow from sensor 1 to sensor 2 (m^3/s)	The propagation velocity of pressure wave between sensor 1 and leak point *Li*(m^3/s)	The propagation velocity of pressure wave between sensor 2 and leak point L*i*. (m^3/s)	Distance from sensor 1 to leak point L*i*(m)	The distance from sensor 1 to sensor 2	The distance from leak point to the pressure sensor 2. (m)	The difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2	Intrusion Detection status [Detected/ Not Detected]
V(m^3/s)	ax_1(m^3/s)	ax_2(m^3/s)	$X_{(km)}$	$L_{(km)}$	L-$X_{(km)}$	$\Delta t_{(Min)}$	
50	**55**	**40**	**10**	**20**	10	**1.8**	Detected
40	**45**	**30**	**10**	**20**	10	**1.85**	Detected
30	**35**	**20**	**10**	**20**	10	**1.8**	Detected
20	**25**	**10**	**10**	**20**	10	**1.6**	Detected
10	**15**	**5**	**10**	**20**	10	**1.3**	Detected

Table 1 The results for single leakage for separation distance 20 km between sensor 1 and sensor 2 and the leakage point is 8 km from sensor 1

The original velocity of flow from sensor 1 to sensor 2 (m^3/s)	The propagation velocity of pressure wave between sensor 1 and leak point *Li*(m^3/s)	The propagation velocity of pressure wave between sensor 2 and leak point L*i*. (m^3/s)	Distance from sensor 1 to leak point L*i*(m)	The distance from sensor 1 to sensor 2	The distance from leak point to the pressure sensor 2. (m)	The difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2	Intrusion Detection status [Detected/ Not Detected]
V(m^3/s)	ax_1(m^3/s)	ax_2(m^3/s)	$X_{(km)}$	$L_{(km)}$	L-$X_{(km)}$	$\Delta t_{(Min)}$	
50	**55**	**40**	**8**	**20**	12	**1.47**	Detected
40	**45**	**30**	**8**	**20**	12	**1.42**	Detected
30	**35**	**20**	**8**	**20**	12	**1.36**	Detected
20	**25**	**10**	**8**	**20**	12	**1.20**	Detected
10	**15**	**5**	**8**	**20**	12	**0.80**	Detected

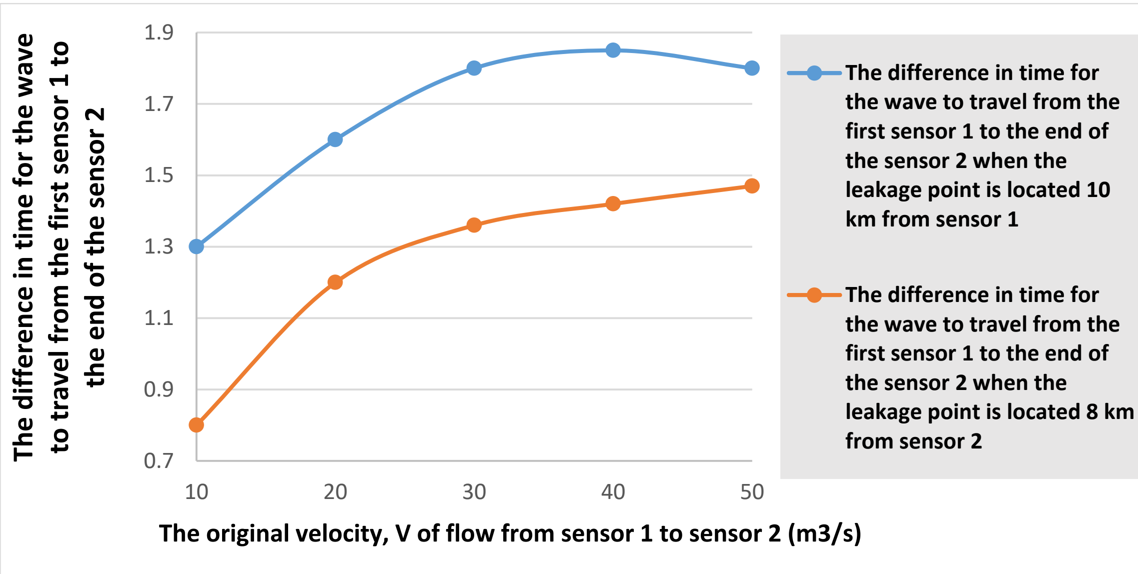

Figure 6 The graph of the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 , $\Delta t_{(Min)}$ versus original velocity of flow, V for single leakage

3.2.2 The Results for Multiple Leakage

The results for multiple leakages are shown in Table 3 (for 2 leakages) and Table 4 for (for 3 leakages). The results for multiple (2) leakages for separation distance d between sensor 1 and sensor 2 are shown in Table 3 and Figure 7.. Given that the distance of first leak L_1 from the second leak L_2 is given by L_1-L_2=n, the mean of distance of leakage from X_1 sensor =n_1 and the mean of distance of leakage for X_2 sensor =n_2, then for leakages 10km and 15km separation from X_1, the value of n_1 = (10+15)/2= 12.5 km. For the same leakage, it will be 10km and 5km separation from x_2 where n_2=(10+5)/2= 7.5. Hence in Table 3 $X_{(km)}$ =12.5 km and L-$X_{(km)}$ =7.5 km. The results also show that the leakage is detected in all the 5 different values of V that were used in the simulation. The results in Table 3 show the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 varied from 2.42 at V= 50 m3/s to 2.00 at v= 10 m^3/s.

Table 3 The results for multiple (2) leakages for separation distance d between sensor 1 and sensor 2

The original velocity of flow from sensor 1 to sensor 2 (m^3/s)	**The propagation velocity of pressure wave between sensor 1 and leak point L*i*(m^3/s)**	**The propagation velocity of pressure wave between sensor 2 and leak point L*i*. (m^3/s)**	**Distance from sensor 1 to leak point L*i*(m)**	**The distance from sensor 1 to sensor 2**	**The distance from leak point to the pressure sensor 2. (m)**	**The difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2**	**Intrusion Detection status [Detected/ Not Detected]**
V(m^3/s)	**ax_1**(m^3/s)	**ax_2**(m^3/s)	**$X_{(km)}$**	**$L_{(km)}$**	**L-$X_{(km)}$**	$\Delta t_{(Min)}$	
50	**55**	**40**	**12.5**	**20**	**7.5**	**2.42**	Detected
40	**45**	**30**	**12.5**	**20**	**7.5**	**2.40**	Detected
30	**35**	**20**	**12.5**	**20**	**7.5**	**2.35**	Detected
20	**25**	**10**	**12.5**	**20**	**7.5**	**2.25**	Detected
10	**15**	**5**	**12.5**	**20**	**7.5**	**2.00**	Detected

The results for multiple (3) leakages for separation distance between sensor 1 and sensor 2 are shown in Table 4 and Figure 7. For 3 leakages, the mean of distance of leakage from X_1 sensor remains n_1 while mean of distance of leakages from x_2 sensor remain n_2. For leakage 1 = 5, Leakage 2 = 10 and Leakage 3 = 15, then;

n_1 = (5+10+15)/3 = 10 km and n_2 = (15+10+5)/3 = 10 km

Hence in Table 3 $X_{(km)}$ =10 km and L-$X_{(km)}$ =10 km. The results also show that the leakage is detected in all the 5 different values of V that were used in the simulation. The results in Table 4 show the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 varied from 1.9 at V= 50 m3/s to 1.34 at v= 10 m^3/s.

Table 4 The results for multiple (3) leakages for separation distance d between sensor 1 and sensor 2

The original velocity of flow from sensor 1 to sensor 2 (m^3/s)	**The propagation velocity of pressure wave between sensor 1 and leak point L*i*(m^3/s)**	**The propagation velocity of pressure wave between sensor 2 and leak point L*i*. (m^3/s)**	**Distance from sensor 1 to leak point L*i*(m)**	**The distance from sensor 1 to sensor 2**	**The distance from leak point to the pressure sensor 2. (m)**	**The difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2**	**Intrusion Detection status [Detected/ Not Detected]**
V(m^3/s)	**ax_1**(m^3/s)	**ax_2**(m^3/s)	**$X_{(km)}$**	**$L_{(km)}$**	**L-$X_{(km)}$**	$\Delta t_{(Min)}$	
50	**55**	**40**	**10**	**20**	**10**	**1.90**	Detected
40	**45**	**30**	**10**	**20**	**10**	**1.86**	Detected
30	**35**	**20**	**10**	**20**	**10**	**1.80**	Detected
20	**25**	**10**	**10**	**20**	**10**	**1.67**	Detected
10	**15**	**5**	**10**	**20**	**10**	**1.34**	Detected

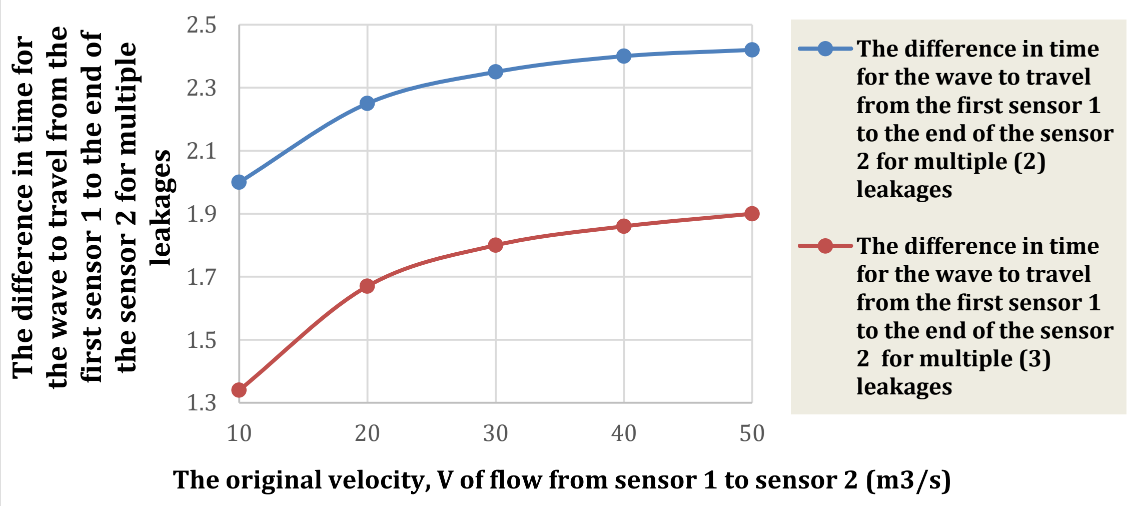

Figure 7 The graph of the difference in time for the wave to travel from the first sensor 1 to the end of the sensor 2 , $\Delta t_{(Min)}$ versus original velocity of flow, V for multiple leakages

4. Conclusion

Mathematical models for the flow in a pipeline with one leakage and with more than one point of leakage is presented. The model was simulated in Proteus virtual system modeling software and the results were presented for the cases on single leakage, double leakage points and triple leakage points. In all, the simulation results show that the mathematical model can effectively be used to detect the occurrence of single leakage and multiple leakages in a pipeline and also be used to estimate the location of the leakage point relative to the sensors.

References

1. Okotie, S. (2018). The Nigerian economy Before the Discovery of crude oil. In *The political ecology of oil and gas activities in the Nigerian aquatic ecosystem* (pp. 71-81). Academic Press.
2. Sambo, A. S. (2009). Strategic developments in renewable energy in Nigeria. *International Association for Energy Economics*, *16*(3), 15-19.
3. Shah, N. K., Li, Z., & Ierapetritou, M. G. (2011). Petroleum refining operations: key issues, advances, and opportunities. *Industrial & Engineering Chemistry Research*, *50*(3), 1161-1170.
4. Klass, A. B., & Meinhardt, D. (2014). Transporting oil and gas: US infrastructure challenges. *Iowa L. Rev.*, *100*, 947.
5. Lukman, A. J. A. O., EMMANUEL, A., Chinonso, N., Mutiu, A., James, A., & Jonathan, K. (2018). An anti-theft oil pipeline vandalism detection: embedded system development. *International Journal of Engineering Science and Application*, *2*(2), 55-64.
6. Kang, J., Park, Y. J., Lee, J., Wang, S. H., & Eom, D. S. (2017). Novel leakage detection by ensemble CNN-SVM and graph-based localization in water distribution systems. *IEEE Transactions on Industrial Electronics*, *65*(5), 4279-4289.
7. Sinha, Rashmi Sharan, Yiqiao Wei, and Seung-Hoon Hwang. "A survey on LPWA technology: LoRa and NB-IoT." *Ict Express* 3.1 (2017): 14-21.
8. Deng, S., Li, J., & Shen, L. (2011). Mobility-based clustering protocol for wireless sensor networks with mobile nodes. *IET wireless sensor systems*, *1*(1), 39-47.
9. Boaz, L., Kaijage, S., & Sinde, R. (2014, July). An overview of pipeline leak detection and location systems. In *Proceedings of the 2nd Pan African International Conference on Science, Computing and Telecommunications (PACT 2014)* (pp. 133-137). IEEE.
10. Zhang, T., Tan, Y., Zhang, X., & Zhao, J. (2015). A novel hybrid technique for leak detection and location in straight pipelines. *Journal of Loss Prevention in the Process Industries*, *35*, 157-168.
11. Wu, H., Qian, Y., Zhang, W., & Tang, C. (2017). Feature extraction and identification in distributed optical-fiber vibration sensing system for oil pipeline safety monitoring. *Photonic Sensors*, *7*, 305-310.
12. Chibuzor, A. S., Chukwujekwu, O. F., & Ekene, O. F. (2014). Oil pipeline vandalism detection and surveillance system for Niger Delta Region. *Month*, *10*.
13. Svelto, C., Pniov, A., Zhirnov, A., Nesterov, E., Stepanov, K., Karassik, V., ... & Laporta, P. (2019, March). Online monitoring of gas & oil pipeline by distributed optical fiber sensors. In *Offshore Mediterranean Conference and Exhibition*. OnePetro.
14. Hirsch, M. W., Smale, S., & Devaney, R. L. (2012). *Differential equations, dynamical systems, and an introduction to chaos*. Academic press.
15. Peyret, R., & Taylor, T. D. (2012). *Computational methods for fluid flow*. Springer Science & Business Media.
16. Liao, S. (2012). *Homotopy analysis method in nonlinear differential equations* (pp. 153-165). Beijing: Higher education press.

17. Simonson, T., Gaillard, T., Mignon, D., Schmidt am Busch, M., Lopes, A., Amara, N., ... & Archontis, G. (2013). Computational protein design: the Proteus software and selected applications. *Journal of computational chemistry*, *34*(28), 2472-2484.
18. Abid, A. J., Al-Naima, F. M., & Ali, A. H. (2018). Comprehensive Modeling of Photovoltaic Array based on Proteus Software. *International Journal of Applied Engineering Research (IJAER)*, *13*(6), 4440-4447.
19. Chen, J., & Yang, S. (2011, July). Application of Proteus software in MCU teaching. In *2011 Second International Conference on Mechanic Automation and Control Engineering* (pp. 6359-6362). IEEE.
20. Liu, L. J., & Li, Z. Q. (2010, August). Design and simulation of LED clock circuit based on Proteus. In *2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering* (Vol. 6, pp. 315-316). IEEE.
21. Lukman, A. J. A. O., EMMANUEL, A., Chinonso, N., Mutiu, A., James, A., & Jonathan, K. (2018). An anti-theft oil pipeline vandalism detection: embedded system development. *International Journal of Engineering Science and Application*, *2*(2), 55-64.
22. Aalsalem, M. Y., Khan, W. Z., Gharibi, W., Khan, M. K., & Arshad, Q. (2018). Wireless Sensor Networks in oil and gas industry: Recent advances, taxonomy, requirements, and open challenges. *Journal of network and computer applications*, *113*, 87-97.
23. Ali, S., Ashraf, A., Qaisar, S. B., Afridi, M. K., Saeed, H., Rashid, S., ... & Sheikh, A. A. (2016). SimpliMote: A wireless sensor network monitoring platform for oil and gas pipelines. *IEEE Systems Journal*, *12*(1), 778-789.
24. Gupta, V. (2021). Recent technologies for leak Detection in Pipeline: A review. *Water and Energy International*, *64*(1), 29-37.
25. Liu, J., Zang, D., Liu, C., Ma, Y., & Fu, M. (2019). A leak detection method for oil pipeline based on Markov feature and two-stage decision scheme. *Measurement*, *138*, 433-445.
26. Reddy, H. P., Narasimhan, S., Bhallamudi, S. M., & Bairagi, S. (2011). Leak detection in gas pipeline networks using an efficient state estimator. Part-I: Theory and simulations. *Computers & chemical engineering*, *35*(4), 651-661.
27. Malekpour, A., & She, Y. (2021). Real-time leak detection in oil pipelines using an inverse transient analysis model. *Journal of Loss Prevention in the Process Industries*, *70*, 104411.
28. Zhang, H., Liang, Y., Zhang, W., Xu, N., Guo, Z., & Wu, G. (2018). Improved PSO-based method for leak detection and localization in liquid pipelines. *IEEE Transactions on Industrial Informatics*, *14*(7), 3143-3154.