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Electronic Monitoring of the Oil and Gas Pipelines (Case Study: Warri Refining and Petrochemical Company Limited)

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Abstract

The Oil and Gas Industry is a significant part of the global economic framework. It plays a crucial role in the energy market as the primary fuel source, generating annual revenue in trillions of dollars globally. Pipeline failures in crude oil transportation can lead to many disadvantages. The Electronic Monitoring of the Oil and Gas Pipelines of Warri Refining and Petrochemical Company Limited (WRPC) was modeled using Matlab Simulink 2017, in real-time using electronic sensors to determine pressure, temperature, motion, mass flow rate, and sound. This model comprises several subsystems; first pipeline subsystem, second pipeline subsystem, third pipeline subsystem, fourth pipeline subsystem, oil theft1 subsystem, oil theft2 subsystem. The results are shown in graphs to identify the changes in the mass flow rate of crude, total crude oil stolen, and changes in crude temperature over pipe length. This study therefore presents the motivation and potential advantages of the proposed electronic monitoring systems that can detect intrusions into the pipelines before vandalism takes place and send sms and email alerts to the control room operators

1. Introduction

The electronic monitoring of oil and gas pipelines uses electronic sensors and devices with associated interfaces to monitor, measure, collect, and respond to phenomenal changes within the designated environment [1]. The designated environment refers to the 8km oil and gas pipelines from the Warri Refining and Petrochemical Company (WRPC) production plant to the Jetty [2]. The high demand for crude oil and refined products, from production to end users, has made pipeline construction and usage essential [3]. Pipeline infrastructure is widely seen as a crucial element for national development, making effective monitoring and protection of pipelines vital for a thriving economy [4]. These pipelines convey flammable materials such as crude oil, refined products, and natural gas which poses certain safety concerns [5]. There have been recorded incidents, fire explosions, and environmental degradation arising from illegal activities of vandals along WRPC Jetty pipelines [6].

Crude oil is distributed by pipelines, from drilling rigs to the crude oil storage tanks, from storage tanks to the refineries for processing, the refined oil and gas from the refinery plant to the products storage tanks, and finally from products storage tanks to the evacuation points like truck loading and the Jetty [7].

The global financial initiative stated that Nigerian crude oil is transported in internationally registered vessels, sold to international buyers, processed by international oil refineries, and paid for using an international bank account [8]. Oil and gas pipelines are priceless assets, often located across vast maritime areas or bridges that are challenging to protect [1]. Attacks or damage to such installations can lead to enormous losses, damage, operational downtime, revenue losses, and chaos in the oil network distribution in the country [1]. Crude oil theft in Nigeria is estimated at around 400,000 barrels per day, resulting in an approximate revenue loss of 1.7 billion US dollars a month, and 20.4 billion a year at 42.5 US dollars per barrel in 2014 alone and the Nigerian Extractive Industries Transparency Initiative said Nigeria lost about 620 million barrels of crude oil valued at $46 billion between 2009 and 2020. The amount stolen is about 7.7 percent of the nation's Gross Domestic Product (GDP) [9].

When an oil pipeline is vandalized, it often leads to leaks that, if not promptly detected, can have severe consequences for the economy, public health, and the environment. Additionally, it results in the loss of valuable products, high cleanup costs, service disruptions, and significant maintenance expenses [10]. This study will present the various pipeline monitoring techniques available in the country and the strengths and weaknesses of each for monitoring activities.

The WRPC and Nigerian National Petroleum Corporation (NNPC) protect the pipelines and installations using their staff, police, host communities, and private security organizations [7].

Pipelines could be the target of vandals, sabotage, and even terrorist attacks. It is popularly the most economical and efficient way to convey large quantities of crude oil, refined products, and natural gas over land [4]. Hence its protection is paramount. Some vandals even bribe their way through the security agencies whose responsibility is to protect the pipeline. Damage to pipeline infrastructure can lead to huge financial losses, ecological damage, operational downtime, man hour losses, huge maintenance costs, and chaos in the oil network distribution [11].

Illegal bunkering is oil taken from pipelines or flow stations, as well as crude oil added to legitimate cargo that is not accounted for [2,3,12].

Nigeria's economy relies on crude oil and other products we could derive from it. It is the country’s main source of foreign exchange [13]. Unfortunately, an important *amount of resources are wasted and lost daily due to vandalism [14].

The federal government has taken bold steps to enhance pipeline security by hiring private security firms, equipping security agencies, and involving host communities. However, these measures have not fully stopped the high rate of pipeline vandalism. Criminal cartels with international ties have emerged as a result [14].

One consequence is that the significant investment in pipeline security remains unaccounted for, and the security measures are considered ineffective. The most common form of oil theft is illegal bunkering, which involves directly tapping oil by puncturing pipelines [3, 15].

It has become a means of livelihood for some individuals who frequently rupture pipelines, using the proceeds for business activities without proper approvals, and for obtaining illegal arms and ammunition [13], violating federal government regulations. The purpose of this study is to address these issues by proposing solutions to secure pipelines through electronic monitoring methods.

Most available security monitoring systems are reactive rather than preventive, hence cannot stop the threat from occurring [16-17]. This is because almost all the earlier pipeline incidents were more of operational leaks and degradation; most devices installed have been mostly used for internal concerns, and not external incursion [18]. This current setup for securing pipelines in Nigeria has existed for over 30 years [1]. Even though this system has been largely unsuccessful, most technologies employed in the 90s are still in use now [16]. Presently, manual patrolling and deployment of armed policemen at designated camps along the pipelines are the methods the company uses to secure their pipeline which is ineffective considering the number of incidents and product losses recorded between 2015 – 2017 [16]. In these three years, the company lost about 4.5 billion liters of various products along her 8km pipelines without any arrest of the vandals [20]. This is against global business best practices and goes a long way to show the weakness of the security system along the pipelines.

The current security monitoring system is very stressful and time-consuming. To monitor and control the oil pipeline efficiently, this electronic method is being proposed using the Supervisory Control and Data Acquisition (SCADA) applications [20].
Several authors have proffered solutions in the best possible way to solve the vandalism problems, but the vandals kept developing new strategies to outsmart their efforts. Hence, there's a need to invent an electronic method that will instantaneously detect and report any intruder, as against the existing methods that are largely compromised and belated reporting.

2. Methodology

The method used in this study involves the utilization of several sensors that collect real-time data from the pipeline networks. Sensors such as pressure, mass flow rate, vibration, motion, sound, and temperature sensors were placed at specific points along the network, then the system employed GPS to locate the pipeline and a GSM module to send notifications. A motion sensor detected human activity within 10-15 meters of the pipeline, followed by a sound sensor that picked up noises from the pipeline when it was struck or from the machinery used by vandals. The vibration and sound sensors worked together to detect vibrations and sounds resulting from the interaction between the vandals' equipment and the pipeline. Pressure and mass flow rate sensors monitored changes at specific points along the pipeline, which occur when tampered with. All sensor data were transmitted to a microcontroller, which relayed the information via the GSM module. Additionally, the exact location of the vandalism was determined using GPS and sent to the relevant authorities through the GSM system.

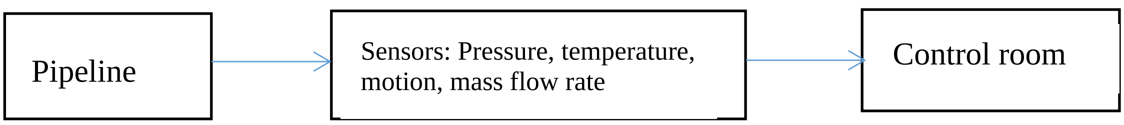

Figure 1: Block diagram of Crude Oil Pipeline Monitoring System

2.1 Pressure

The pressure of the crude is the force applied per unit area thus affecting acceleration. It can be expressed in the following simple formula in equation (1)

$P = \frac{F}{A}$[20] (1)

where
F is force
A is the area it acts on
The pressure beneath the crude equals the product of the crude's density, the acceleration due to gravity, and the depth (height) below the specific point as shown in equation (2). Pascal (Pa) is the unit of pressure.

$P = \rho g h$

where (2)

P represents pressure (Pa), ρ stands for the density of a crude (kg/m^3), g is the acceleration due to gravity (9.80 m/s^2), and h is the height of a column of gas or fluid (m)

2.2 Temperature

The temperature in this case refers to the losses due to the flow of crude which is shown in equations (3) and (4).

$$Q_{under\ ground} = \frac{T_{crude} - T_{under\ ground}}{R_{conduction,\ under\ ground} + R_{convection,\ under\ ground}} \text{ [11]} \qquad (3)$$

$$Q_{surface} = \frac{T_{crude} - T_{surface}}{R_{convection,\ surface}} \text{ [11]} \qquad (4)$$

Hence, the total heat loss is obtained:

$Q_{total} = Q_{under\ ground} + Q_{surface}$

While this calculation does not consider heat loss due to radiation and evaporation, it is evident that the impact of these factors will be minimal. The insulated pipe is divided into small segments, with each segment maintaining a certain temperature as shown in Figure 2.

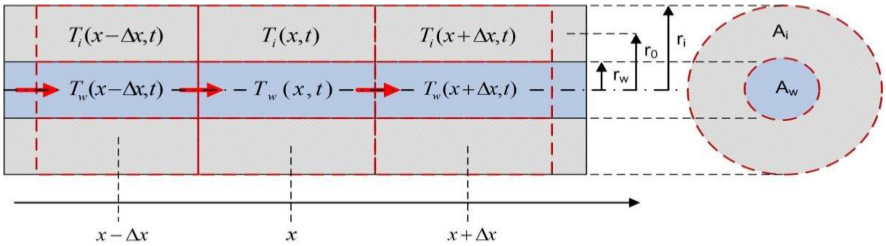

Figure 2: Finite element grid of the insulated pipe

Ti = temperature of the insulation
Tw = temperature of the crude
Ai = cross-sectional area of the insulation
Aw = cross-sectional area of the pipe

As Δx becomes very small, the temperatures of nearby sections can be estimated using linearization as shown in equations(5) and (6).

$$T_i(x-\Delta x,t) \approx T_i - \Delta x \frac{\partial T_i(x,t)}{\partial x} \qquad \text{[11]} \qquad (5)$$

$$T_i(x+\Delta x,t) \approx T_i + \Delta x \frac{\partial T_i(x,t)}{\partial x} \qquad (6)$$

The insulation is expected to significantly minimize ambient heat loss, allowing us to disregard it. Additionally, despite minor heat losses, the crude temperature within the pipe is assumed to be the same, averaged between the tank temperature, $T_{in}(t)$, and the (unknown) outlet temperature, $T_{out}(t)$. Likewise, the insulation is assumed to have a uniform profile. Under these assumptions, the x-dependence is eliminated. This greatly simplifies the model with minimal loss of accuracy, as demonstrated in Figure 3.

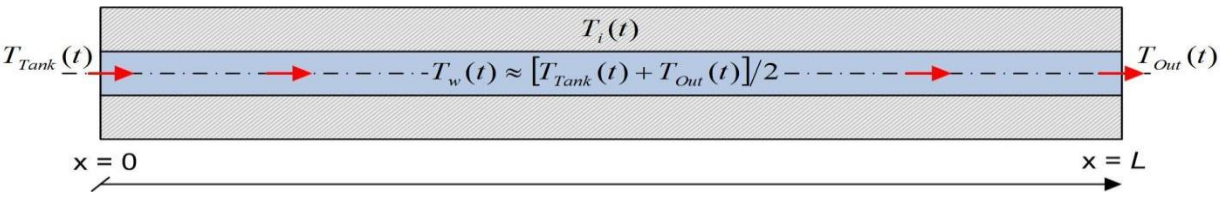

Figure 3: Insulated pipe with simplified temperature distribution

By expressing the heat loss from the crude as the total heat transferred to the insulation, the following equation (7) is derived :

$$\rho wcp,wq(t)\left[T_{in(t)} - T_{out}(t)\right] = \frac{2\pi k_i}{\ln(r_0/r_w)}\left[\frac{T_{in}(t)+T_{out}(t)}{2} - T_i(t)\right] \quad (7)$$

This transferred heat results in a rise in the insulation temperature, as ambient heat loss is assumed to be negligible, as demonstrated in equation (8):

$$\frac{2\pi k_i}{\ln(r_0/r_w)}\left[\frac{T_{\tan k}(t)+T_{out}(t)}{2} - T_i(t)\right] = \rho_i cp,iA_i\frac{\delta T_i}{\delta t} \quad (8)$$

Because the flow and temperature of the crude change over time, it's difficult to solve these equations exactly. However, since the insulation reacts slowly to changes, the flow rate changes much faster than the insulation can adjust. This means that quick changes in flow won't significantly affect the insulation temperature. Instead, we only need to consider the average flow over a period that matches how quickly the insulation responds. This average flow, q_{av}, gives us a steady temperature, T_{av}, for the crude. With this approach, we can solve the equations, (7) and (8) more easily.

2.3 Motion

The mean velocity/speed of moving crude was calculated using equations 9

$v = s/t$ [20] (9)

where

v = velocity or speed (m/s)

s = linear distance traveled (m, ft)

t = time (s)

Distance is the total length of the path traveled by an object from one point to another. The displacement is the straight-line distance between the object's starting and ending points, in contrast to distance which refers to the actual path traveled.

We often use velocity and speed interchangeably, but it's important to understand their differences. Speed measures how quickly a distance is covered, indicating the rate at which distance is traveled. In contrast, velocity is a vector that not only defines how fast or slow a distance is traversed but also encompasses the direction of travel.

You can derive velocity, if acceleration stays the same, using the following equation 10:

$v = v_0 + a t$ [20] (10)

where

v_0 = initial linear velocity (m/s, ft/s)

a = acceleration (m/s^2, ft/s^2)

If acceleration is constant, you can calculate the linear distance using the following formula 11:

$s = v_0 t + 1/2 a t^2$ (11)

Integrating (10) and (11) to state the final velocity as shown in equation 12:

$v = (v_0^2 + 2 a s)^{1/2}$ (12)

When velocity changes over time, it can be expressed as:

v = ds / dt [11]

where

ds = change in distance (m, ft)

dt = change in time (s)

Acceleration is then given as shown in equation 13:

a = dv / dt (13)

where:

dv = change in velocity (m/s, ft/s)

2.4 Mass Flow Rate

The mass flow rate of crude is used to determine how quickly a mass of crude moves through a specific area. The rate is influenced by the crude's density, how fast it's moving (velocity), and the size of the cross-sectional area.

Imagine mass in motion - that's what mass flow rate is all about. It's like the transport of mass over time. We measure it in kg/s and the equation for deriving the mass flow rate is provided in equation (14):

Mass Flow Rate = (density)*(velocity)*(area of the cross-section)

$$m = \rho\ v\ A \tag{14}$$

We have:

ρ = Density of the fluid

v = Velocity of the fluid

A = Area or cross-section

2.5 Dynamic Model

The dynamic models of the outlet pipe are governed by a sensor for temperature, pressure, motion, and flow rate. This was modeled using the Matlab 2017 version.

2.5.1 Pipeline Subsystem

The Simulink model for the pipeline subsystem is shown in Figure 4.

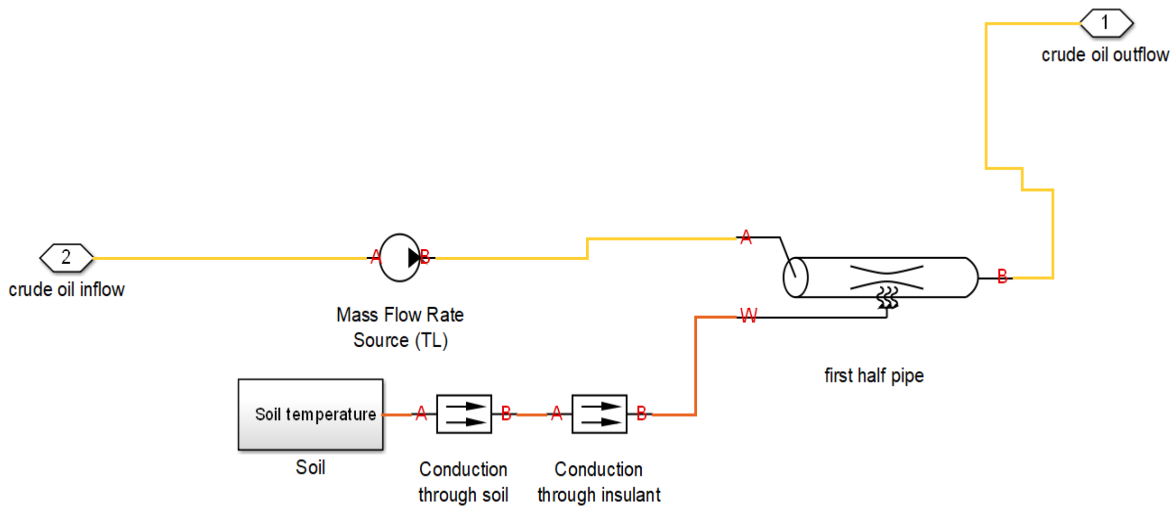

Figure 4: Simulink model for the pipeline subsystem

The mass flow rate equation for crude flow is shown in equation 15:

$$V_{dot} * r_{ho0} \tag{15}$$

Where V_{dot} is the volume of crude flow per second and r_{ho0} is the density of crude oil,

The cross-sectional area of the pipeline was modeled as shown in equation (16):

$$\pi \times Dl^{2}/4 \quad [20] \tag{16}$$

Where Dl is the diameter of the pipe

In this model the following crude oil properties were considered, listed in Table 1.

Table 1: crude oil properties considered in the model

Crude Properties
Kinematic viscosity
Pressure
Isothermal bulk modulus
Internal energy
Temperature
Specific heat at constant pressure
Thermal conductivity
Density
Isobaric coefficient of thermal expansion

The Simulink model for the monitoring of the crude oil pipeline is shown in Figure 5, the model is comprised of several subsystems;

i First Pipeline subsystem
ii Second Pipeline subsystem
iii Third Pipeline subsystem
iv Fourth Pipeline subsystem
v Oil Theft1 subsystem
vi Oil Theft2 subsystem

Each of these subsystems is terminated with several sensors, to help monitor the output result of the systems. Pressure, temperature, and mass flow rate sensors were employed. Each of these subsystems was modeled with the help of several equations to help accurately describe the processes that go on along a crude pipeline. The temperature changes along the line were also considered. The principle of operation of the model is as follows, crude oil flows from the upstream segment into the first pipeline subsystem (which is assumed to be composed of a network of pipelines), the crude oil is then measured using a mass flow rate sensor to determine the mass flow rate of the subsystem, this information is then sent to the control room (which is modeled as a display scope), It is then assumed that there is a crude oil theft at the output of the subsystem, this theft was modeled with the help of a ramp signal which signifies the cross-sectional area of the theft region. This ramp signal is gradually varied to get the desired theft cross-sectional area.

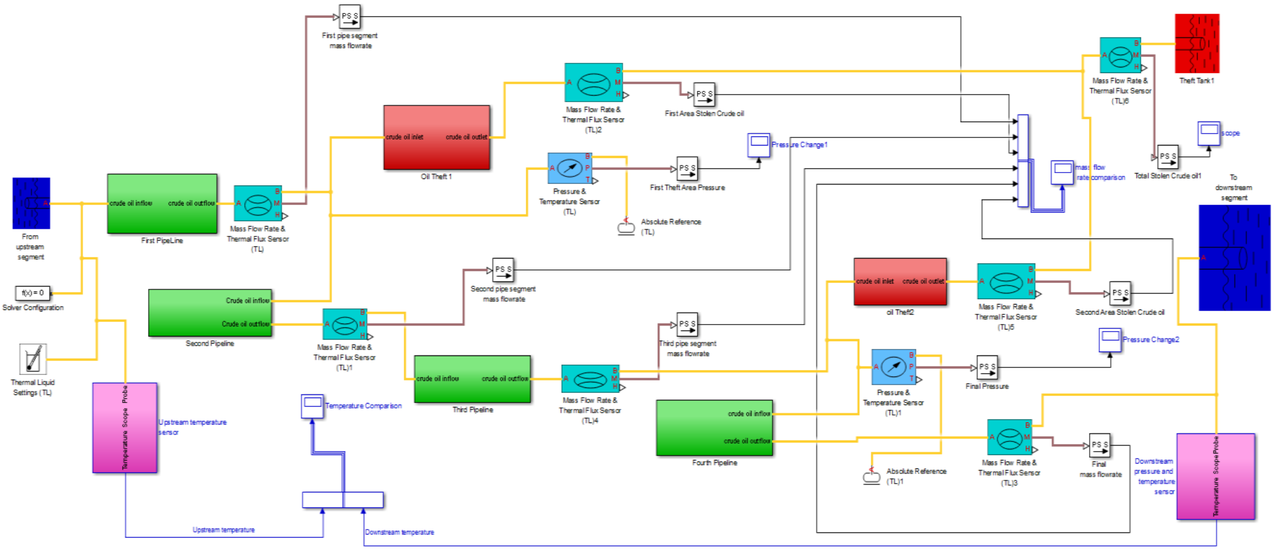

Figure 5: Complete Simulink Model of Crude Oil Pipeline Monitoring System

The pressure at this point is also measured with the help of pressure sensors, as it is assumed there would be changes in the pressure of crude flow as a result of the theft. The crude oil then flows to the next pipeline subsystems where several oil thefts were also simulated.

3. Results and Discussion

3.1 Results

This research exposes the weaknesses of the traditional method of oil and gas pipeline monitoring adopted by WRPC to monitor/safeguard the pipeline infrastructure and presents electronic method as a better alternative or to complement the existing system of pipeline infrastructure monitoring. The following results were obtained from the simulation as shown in Figures 6 to 11.

The graph in Figure 6 shows the changes in the mass flow rate of crude oil along the pipeline network, the Initial mass flow rate of crude oil from the upstream sector was 210Kg/s (This value was determined using the mass flow rate equation and diameter of pipeline), at simulation time 0s and 1000s, there was theft of the crude (yellow and light blue curve), these theft reduces the initial mass flow rate of crude from 210Kg/s to 134Kg/s, and finally to 98Kg/s. This data is transmitted in real-time to the control room for proper action.

The graph in Figure 7 shows the total volume of crude oil stolen, we observe that from the initial mass flow rate of 210Kg/s, about 112Kg/s of crude was lost as a result of crude theft, hence the system provided real-time monitoring of the pipeline network.

The graph of Figures 8 and 9 shows the shifts in the pressure of crude oil along the pipeline. We observe that at the theft times (0s to about 2000s), the pressure of crude flow gradually drops from about 3200 bar to about 1.2bar as a result of oil theft, this is by a well-established theory which tells us there would be a decrease in pressure along a pipeline when an artificial outlet is created along that pipeline. This data would be transmitted in real-time to the control room, where further actions will be taken.

The graph of Figure 10 shows the shift in the temperature of crude oil along the pipeline. We observed that the temperature of crude oil gradually drops along the pipeline, this is by simulated environmental changes along the line. This data would prove vital in the event of a fire outbreak along the line, it would help notify the necessary authorities for an immediate course of action.

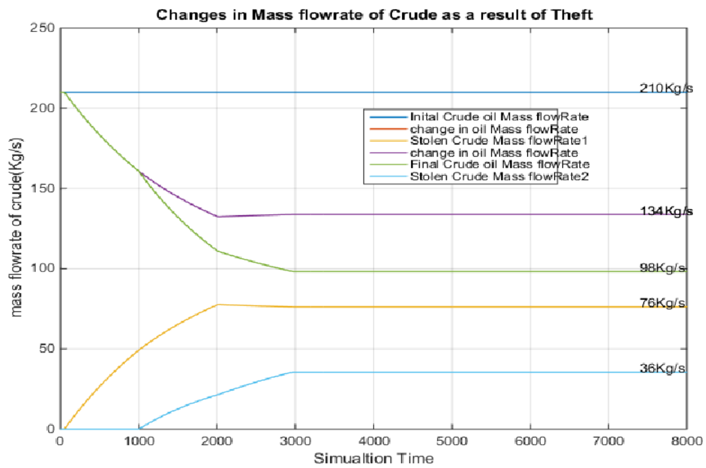

Figure 6: shows the changes in the mass flow rate of crude oil.

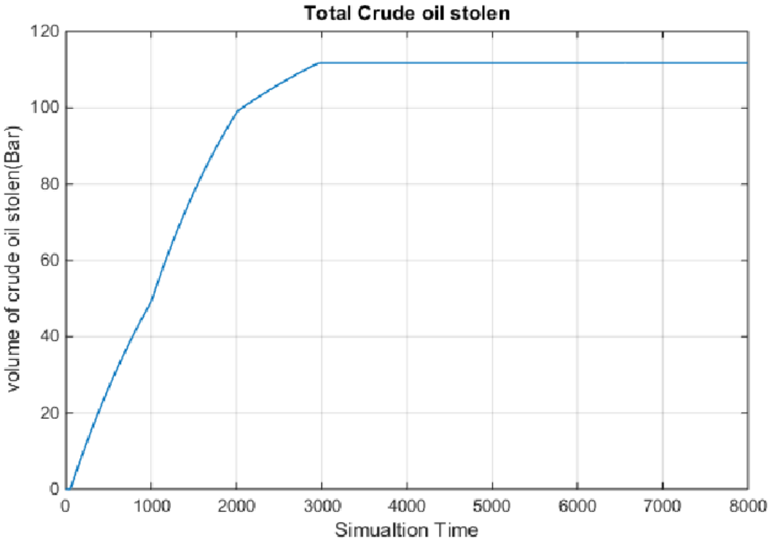

Figure 7: Total crude oil stolen

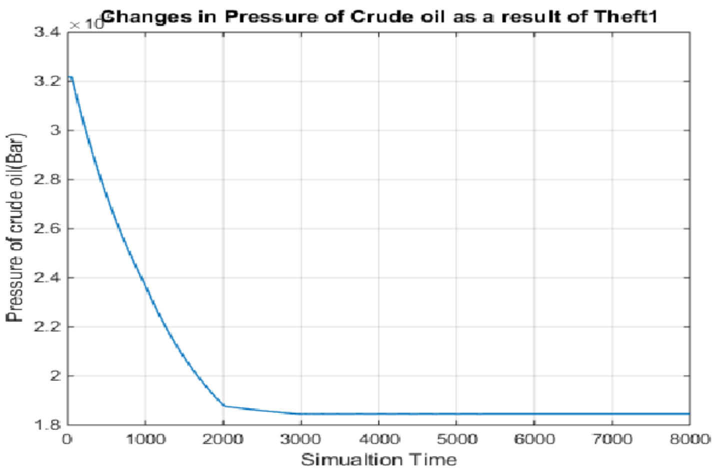

Figure 8: Change in pressure of crude oil as a result of theft1

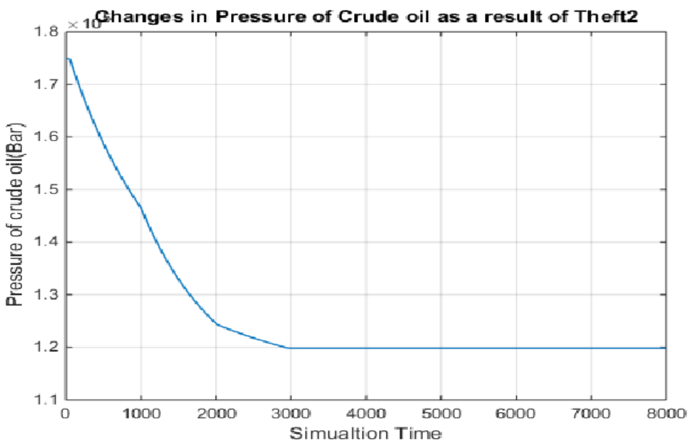

Figure 9: Change in pressure of crude oil as a result of theft2

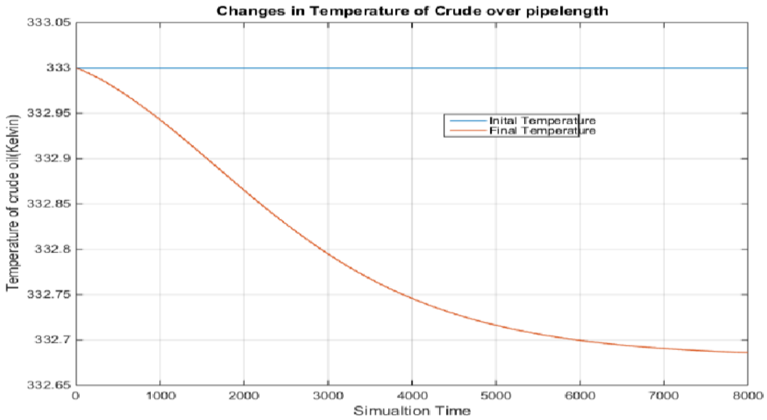

Figure 10: Changes in temperature of crude over pipe length

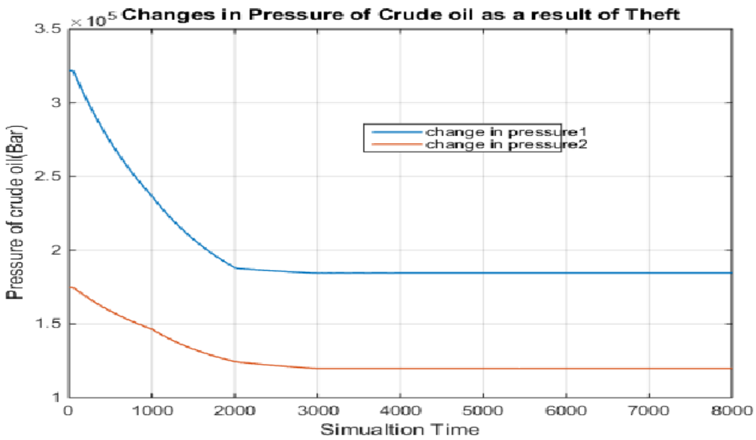

Figure 11: Changes in pressure of crude oil as a result of theft

3.2 Discussion

This study highlights the shortcomings of current monitoring methods and introduces electronic monitoring as a superior alternative for overseeing oil and gas pipeline infrastructure. The proposed electronic monitoring system involves separation of the pipeline into segments with overlapping network coverage, all interconnected by wireless communication unit sensors. Each sensor is responsible for collecting data from its surrounding environment and transmitting it to the control center through communication links.

Compared to other monitoring systems, the electronic model addresses the reliability issues of existing methods and offers real-time monitoring of pipelines, aiming to eliminate vandalism along oil and gas pipeline routes. Unlike the existing nature, the failure of one video camera does not affect the connectivity due to the overlapping nature of the network coverage areas.

4. Conclusion

This study provides insight into ways an electronic monitoring system can be used to detect, alert, and dispatch an alarm of an oil and gas pipeline vandalism incident from a remote location to the control center using the model.

A method for providing automated intrusion detection for pipelines with remote monitoring and location specification was achieved. A sensor was used to detect early intrusion of vandals into the pipeline facility and communicate to the operator via sms, emails, or alarms so that a preventive action can be initiated such as shutting down the pipeline valve or calling in the security agents for the arrest of the criminals. The benefits of the study include early detection of intrusions, and prompt reporting to the control center during the time pipelines are being damaged, thereby reducing financial losses, environmental degradation due to the attendance leakages, possibly fire outbreak, and the possibility of arresting the vandals.

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