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Design and implementation of an oil leakage monitoring system based on wireless network

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ABSTRACT

Monitoring pipeline leaks is one of the recent hot studies. Leakage may occur because of time corrosion in the tube raw materials. To reduce the negative consequences of this leak, an effective leak detection system is used to prevent serious leakage accidents and damage in oil pipelines. Buildings, ecosystems, air pollution, and human life are all at risk in case of leakage occurs which could lead to fires. This paper introduces one of the research methods for the detection of pipeline leaks with a particular focus on software-based methods. The computer board interface (CBI) and wireless sensor networks have been used beside Arduino as a micro-monitor for the entire system. ZigBee is also utilized to send read data from sensors to the monitoring system displayed on the LabVIEW graphical user interface (GUI). The operator can take direct action when a leak occurs. The effectiveness of the leakage monitoring process and its practical use are demonstrated by the introduction of computerized techniques based on pressure gauge analysis on a specific pipeline in the laboratory. The result showed that the system is widely covered, accurate data transmission and robust real-time performance which reduces economic losses and environmental pollution.

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1. INTRODUCTION

A pipeline's network is one of the essential means to transport oil for long distances in most countries, such as Iraq. This network has faced numerous issues, leakage is the most regular challenge that requires practical solutions. A wireless sensor network could be used to quickly and accurately detect leaks that may occur in the network. In economic terms, pipelines work properly without any leaks if they are properly maintained and monitored. The most frequent leaks occur because the maintenance of the oil pipeline is not properly conducted. Especially, at low points of the pipe where moisture accumulates, or sites with defects in the tube. However, such faults can be recognized by examination and correction tools before they develop to the leakage stage. Other causes of leakage include accidents, terrorism, and sabotage. Moreover, the risk of leakage increases with the ageing of pipelines [1]. Assisting pipeline controllers in revealing and leaks determination is the essential purpose of leak detection systems [2]. These systems also enhance productivity and reliability by minimizing downtime and pipeline unloading time. The use of a high-precision measuring instrument provides very reliable and accurate results for handling simple scanners. With step-by-step instructions, measurements and checks that meet legal standards are very easy. Potential accidents of oil damage can be effectively prevented by regular examination by experts, as small leaks can be detected early and corrected. The leakage rate scale is used for this important task [3].

Several papers focus on address the issue of leakage whether in water or oil or gas [4]–[8]. In [9], a discussion was placed to design a system to monitor leakage in the water pipes with a large diameter is conducted. The optical fiber sensor system is distributed in this paper according to Brillouin scattering. The design and implementation of a certain infrastructure have allowed conducting a set of tests that demonstrates the capability of the suggested scheme to be done successfully. In [10], [11], the designed a locating and monitoring system to solve the problems of leakage in the water supply networks and underground boosters by using the general packet radio service (GPRS)/global system mobile (GSM) technology. The data is transmitted by GPRS/GSM network, so the condition of the tap water pipe network is monitored by Web software. The result shows the efficiency of the system in detecting and indicating the location of leakage in the network. In [12]–[14], a wireless sensor system is utilized to detect leaks in metallic oil pipelines in an industrial environment. The mechanism of the proposed system depends on observing the changes in produced sound signals due to a leakage effect. To reduce cost and increase the range of sensors, low frequencies are used to detect and characterize leakage. Numerous other papers [15]–[19] are addressed the same topic and method detection leakage but in different methods.

In this work, a professional scheme has been proposed to conduct leakage detection in oil pipelines. The proposed system is developed as an innovative leakage detection product and its location on pipelines. The leakage monitoring system is further developed using the power of rapid computing by a wireless sensor network (WSN) to adapt the conditions prevailing in Iraq. Thus, simulation of a pipeline model using graphical user interface (GUI) is accomplished without neglecting its real-time operations on a computer. The current sensors, measurement technology, climatic conditions and pressure increase should have been considered by the medium pumping station in the monitored section. The improved method should be used to apply a pipeline model and test it for practical application. Each individual sensor provides rapid checks, high-precision values, and tube compatibility. Besides, the ideal data storage is the computer, which can be used in various locations. The proposed system is used to control oil pipeline leaks using pressure sensors. When the pressure in a part of the pipeline is reduced below a certain level, the sensors of this system automatically detect this phenomenon remotely. These sensors operate at 5 V DC. The sensor's input and output voltage are 0.5-4.5 V DC and can be easily connected to an Arduino without using any voltage transducer because Arduino operates at 5 V. It senses a pressure range of 0-1.2 Mpa.

The importance of the research lies in the use of wireless sensors to detect leakage in oil pipelines, as well as to control and determine the appropriate protocols for them, and to implement a model that covers part of the practical aspect in educational laboratories. Reducing the cost of available data systems through the use of software and open source technologies in design. The essential goals of this project are to develop a technique for speculation leakage location and rate, through introducing a model to mimic leak detection in an oil pipeline carrier using a new technique based on a wireless sensor network. This model is converted to computer software for estimating leakage location and spill average. The outcomes of this paper are anticipated to introduce a novel contribution to the early detection of oil spills in the petrol fields.

2. MODEL-BASED LEAK DETECTION

The design approach for pipeline leakage detection is utilized by this research. Firstly, developing the pipeline model and supply it with pressure sensors that are installed at the pipeline ends. Then, the user interface is used to compare the flow rate between real and simulated pipelines. If the difference exceeds the specified value, it means that the leak was detected. For leaking infusion, a scheme is used according to the rule that the pressure drop is linear along the pipeline. Two pressure devices are installed at both ends of the tube. From the slopes of their measurements on both sides, a leaking infusion can be calculated. The intersection of the lines with these two different slopes represents the leak site, and this is how the leak is estimated. Figure 1 shows the overall network model of the wireless sensor network architecture. It consists of the pipeline that communicates with the network in a dedicated and wireless manner to send its messages to a remote computer via a base station [20]. While Figure 2 provides an overview of the proposed method [21]. There are many methods for detecting leakage in pipelines. Model-based leak detection system represents a specific group of systems and aims to improve accuracy to achieve desired results. The paper explains how optimal results can be achieved using typical leak detection systems adapted to individual application conditions. Using several practical examples that illustrate the highly variable preconditions, the potential capabilities of a leak detection system will be presented. At the top of these conditions, it will be considered in a model-based leakage recognition system which is based on pressure and flow readings at the inlet and outlet of the pipeline.

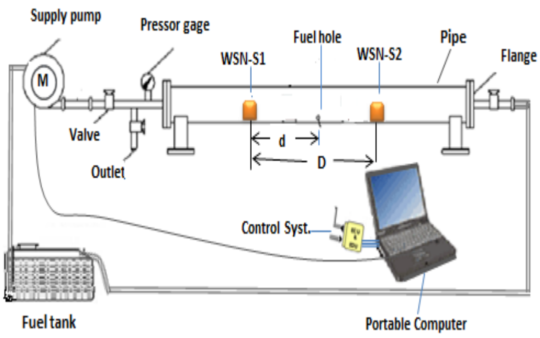


Figure 1. The physical model for a pipeline leakage

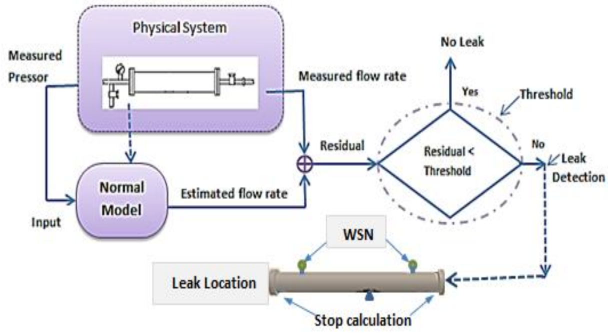


Figure 2. Overview of the proposed scheme

3. HARDWARE AND SOFTWARE SYSTEM

The proposed plan is a treatment system capable of monitoring and controlling the parameters of oil through the use of the Arduino system and the WSN sensor module. The main goal of leak detection systems (LDS) is to help the pipeline supervisors to detect and locate leakage [7]. In this paper, we will cover the process of setting up oil leakage monitoring system devices using Arduino and ZigBee to integrate components and to create required tools and make the connection between hardware parts with program commands to obtain the wireless sensor and actuators. This system consists of many features, such as the monitoring system built by LabVIEW GUI, the ZigBee transceiver used to observe oil concentration, and an alarm system to alert the user. In addition to these, the control system contains an Arduino Uno class controller, oil leakage sensors, valves, WSN sensor, water pump, and electrical relays to control the activation of the devices.

3.1. Hardware design

The proposed system consists of two main units: First, the control unit and the monitoring unit. The control part contains three main components: a sensor unit that holds the pressure sensor, Arduino Uno controller and the ZigBee communication unit. While the second part is a monitoring module, which consists of a ZigBee module and a computer supplied with a GUI window created with MATLAB 2018 software. Figure 3 shows the block diagram of the suggested system [21].

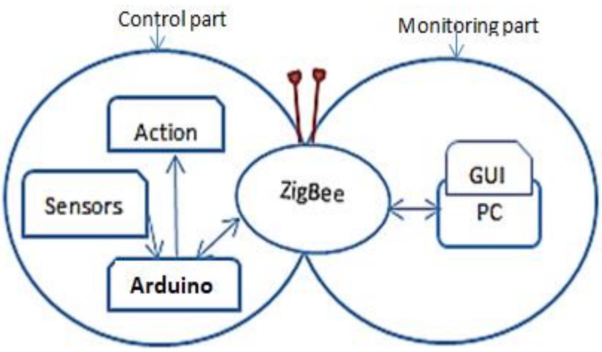


Figure 3. Block diagram of the proposed system

3.1.1. Monitoring and control part

The system monitors the oil pipes by detecting the parameters utilizing sensors. The sensor module (WSN) gathers the data by the pressure sensor. Next, the sensor modulates the data signal and then transmits it to the control unit. The control unit (Arduino Uno) processes the data using the stored algorithm and delivered the data to the Monitoring Part. In this section, the ZigBee acts as a sender of the recorded data to the base station. The base station collects data using the ZigBee module which behaves here as a receiver. After gathering the information, this entry will deliver it to the computer using the predefined interface. The computer presents the information by a GUI designed by MATLAB 2018 software where the data is monitored and analyzed by the user. The system in the control part monitors the pressure parameters according to instructions sent from the base station. The operator decides to monitor and analyze the information. If the data reflecting the parameter values falls within the permissible limits in the safe zone, no action is required by the operator. In contrast, if the parameter values reach the hazardous limits, the operator conducts decisions utilizing the information demonstrated on the graphical user interface. The user delivers instructions through a set of control switches in the GUI, as they either turn the control systems on or off. At the same time, the Arduino can automatically decide according to the pre-saved algorithm.

3.1.2. Software-based systems

The core method operates by monitoring the pipeline parameters (flow, pressure, and temperature). When a leak is detected, an immediate drop is recorded at the location of the leak which produces a wave of negative pressure. This wave propagates towards the upstream and downstream of the pipeline at a specific velocity. Both the beginning and the end stations of the pipeline are supplied with two pressure sensors. The pipeline leak is identified by sensing the negative pressure wave using the installed two sensors and the leak location is located by calculating the pressure difference between the appearance times of the negative wave at each end. Figure 4 shows the program flowchart which mainly consists of two parts, a control unit and an alarming side. It is intended to give a general idea of the flowchart and the implementation of the program. Figure 4 shows the scheme of work of the program according to the following steps: In the initial state, the program determines the position of the oil flow in the pipe and the pressure level from the pressure transducer then the message nodes box of the (node part1, node part2 and node part3) is determined. Next, check if the pressure level is less than the setpoint, no message will be displayed for this situation. However, when the pressure drops and the pressure difference increases between the sensors (S1 and S2), a low pressure message is sent through the GSM module to the main node then the low pressure is displayed from the field node location and an alarm sound is fired. To monitor an oil spill online, the LabVIEW runtime engine must be installed in the client computer to display and control through the monitoring system as shown in Figure 4. The overall performance of the model was managed and linked to the LabVIEW software. The name of the VISA resource in LabVIEW was set to the specified setting and the information transfer rate was set in the communication channel (baud). The baud rate is commonly used when discussing electronics that use the serial port. For this model, it uses a "9600 iPod" meaning that the serial port is capable of transmitting a maximum of 9600 bps from Arduino and ZigBee [22].

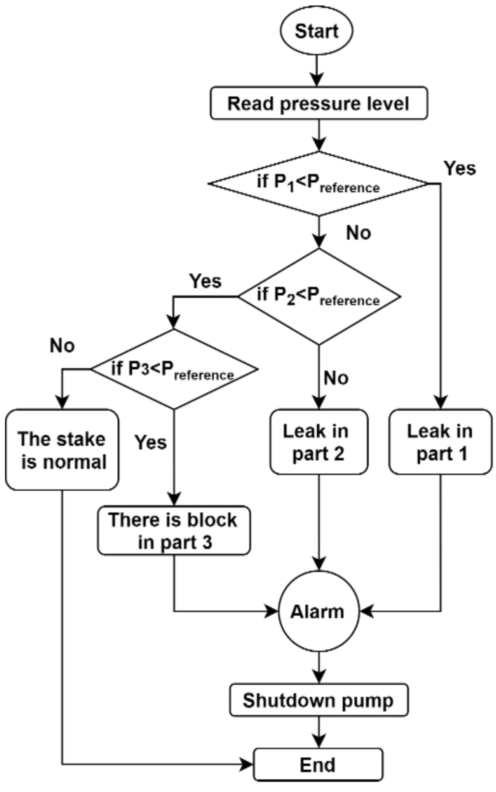


Figure 4. The program flowchart

4. THE DEVELOPMENT OF MATHEMATICAL MODELING

A mathematical model aside with WSN method model is used to address the issue of the oil pipeline. The hole diameter of the leakage represents the leakage size, and the diameter can be altered to demonstrate the leakage hole matched with the pressure drop along the mainline. The mathematical model of a network pipeline will be represented by connecting the single-phase oil pressure drop in the pipeline to determine the friction factor. According to this model, pipeline leakage can be replicated using various leakage situations (leak location and rate). The model will be utilized to calculate the pressure spreading along the pipe beneath normal circumstances (no leakage) [23]. The further derivation of the mathematical model results includes the following assumptions: i) the main pipeline is treated as one piece with only one leakage hole in the pipe, ii) the oil flow is constant and horizontal, iii) the oil flow can be laminar or turbulent, and iv) the study adopts the change in pressure as the flow is isothermal.

Figure 5 shows the derivation of the developed model with one leakage hole. Oil's gravity, pressure, and temperature at the inlet are vital properties and required to compute the pressure drop. For the flow of oil in the tubes, where the tube diameter is D, the length is L. If the oil has a particular thickness and speed, the pressure drop along the tube can generally be symbolized by (1) and (2).

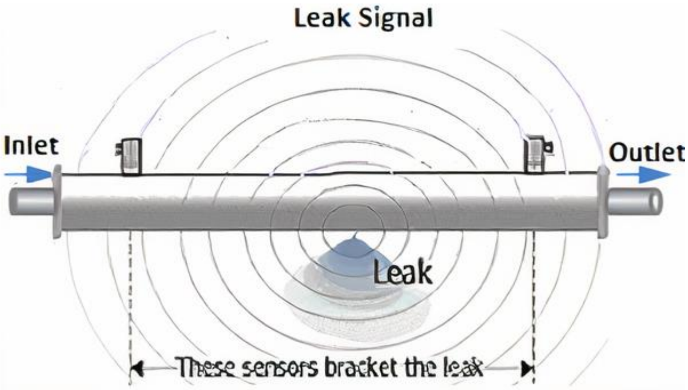


Figure 5. A pipeline segment with one leak

To make sure oil flow in the tube, the mass conservation (1) and the momentum conservation (2) must be applied as [24]:

$$\frac{\partial \mathrm{p}}{\partial \mathrm{t}} + u\frac{\partial \mathrm{p}}{\partial \mathrm{x}} + \rho c^2\frac{\partial \mathrm{u}}{\partial \mathrm{x}} = 0 \quad (1)$$

$$\frac{\partial \mathrm{u}}{\partial \mathrm{t}} + u\frac{\partial \mathrm{u}}{\partial \mathrm{x}} + \frac{1}{\mathrm{p}} * \frac{\partial \mathrm{p}}{\partial \mathrm{x}} = 0 \quad (2)$$

For (x, t) ∈ (0, L) × (0, ∞) and where p(x, t) is pressure and $u(x, t)$ is flow velocity and ρ(x, t) is density. The relation between density and pressor is modelled as (3):

$$\rho(x, t)=\rho_{ref} +(p\ (x, t) - p_{ref})/c^2 \quad (3)$$

where c is the speed in the fluid and ρ_{ref} is the reference density at a reference pressure.

4.1. Determining flow types of Reynold's number (R)

The fluid flow is calculated to be laminar or turbulent using the dimensionless Reynold's number and according to the set of properties such as speed, length, thickness and the kind of flow. It is stated as the ratio of inertial powers to viscous forces and can be described as units and parameters respectively, as (4):

$$\mathrm{R} = (\rho.\mathrm{v}.\mathrm{d})/\mu \quad (4)$$

where ρ =fluid density (kg/m3), μ =absolute viscosity of fluid (Pa-s), d =diameter of pipe in (m), and v =average velocity of the fluid. Reynold's number is dimensionless When Turbulent flow: R>4000 while Laminar flow: R<2000, and Transition flow: 2000<R<4000.

4.2. Computing average velocity

Velocity profile changes across the cross-section of pipes. In practice, we are usually dealing with a turbulent flow. In addition to the Reynolds number, the wall roughness also plays a decisive role, i.e., the determination of the speed course and later the pressure loss in a purely theoretical way is no longer possible. Even with the turbulent flow, the liquid adheres to the pipe wall. Velocity build-up is parabolic as in laminar flow. However, the course is significantly flattened in the turbulent flow region show in Figure 6 [25].

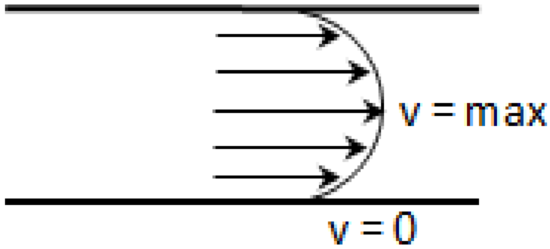


Figure 6. Velocity profile changes across the section of pipes

4.2.1. Laminar flow equations

Velocity distribution:

The equation of velocity $v = Q/A$ (5)

As the tube diameter is typically given: $v = (4.Q)/(\pi.d^2)$ (6)

where A=area of pipe (m^2), Q=flow (m^3/s), d=pipe diameter (m)

To find out the problem of pressure loss in static and incompressible flows, a guide for the basic calculation of a straight pipe of constant diameter is provided and the application is shown using a working example: Oil flows in a horizontal when a temperature is 15 C, 1 cm diameter tube with a flow rate of 9.42 L/min. The length of the pipe is 10 m. Find Reynold's number, the resistance of flow, and the pressure drops in the pipe.
Convert all units into SI units,

$d = 1\ cm = 0.01\ m$, $Q = 9.42\ L/min\ (1.6667x10^{-5}\ m^3/s/L/min)$, $Q = 1.57x10^{-4}\ m^3/s$
Average velocity: $v = 4Q/\pi d^2$=$4(1.57x10^{-4}\ m^3/s)/\pi(0.01\ m) = 2.0\ m/s$
if $\rho = 880\ kg/m^3$, $\mu = 0.160$ Pas then

Compute Reynold's number is:

$R = \rho.v.d/\mu = ((880\ Kg/m^2).(2\ m/s).(0.01\ m))/(0.160\ Pas) = 109.95$
$R < 2000$ so flow in Laminar. A linear relationship between flow and pressure drops.

4.2.2. Turbulent flow equations

Equations of turbulent flow for round pipes:

$P = K_t.Q^2$ (Pas) (7)

$v = (8.\rho.f.l)/(\pi^2.d^2\ )$ (Pas/m^3) (8)

$Rt = 2.K_t.Q$ (9)

where: f=friction factor, l=length (m), d=diameter of pipe (m), r=liquid's density (kg/m^3), and R_t=turbulent flow resistance (Pas/m^3) , p=pressure (Pa), Q=flow (m^3/s)

In the turbulent flow region as shown in Figure 7. In this area, the pressure loss depends on the Reynolds number which as we know, is a function of velocity. There are different empirical formulas for specific regions of the Reynolds number.

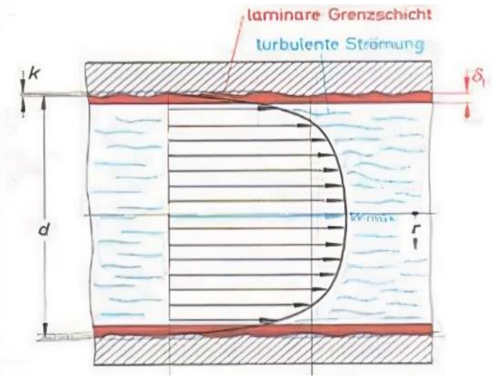
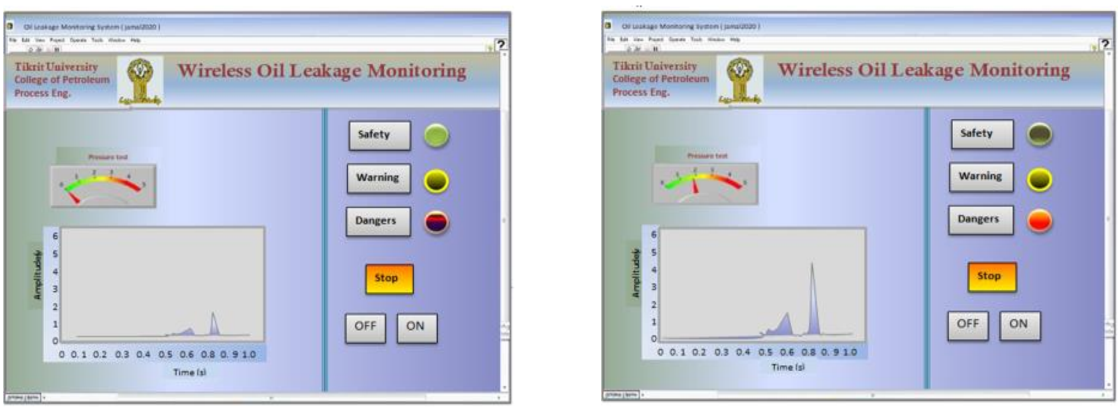


Figure 7. Turbulent flow region

5. MONITORING SYSTEM DURING THE TEST

The personal computer (Pc) panel interface is utilized for an improved graphic representation for a control system and delivers a real-time data acquisition. This increased productivity by providing a friendly user interface, also screens can be resized and have higher resolutions, which facilitate the operation of observing the equipment by the user. Leakage position and leakage rate are two pipeline leak factors that must be precisely defined to cope with pipeline leakage issues. The study relied on these two parameters through the development of the oil transportation pipeline model and the leak detection model that was built using the WSN. While the wireless sensor system and the Arduino controller depend on the mathematical approach and actual leakage data. The model has been tested with an oil leakage system, the presence of oil leakage has been successfully detected according to the variation of the pressure outputs. Based on the GUI, the pressure gauge and oil tank are available to assist the user to monitor the level of oil leakage. Figures 8(a) and 8(b) illustrate the three-stages oil spill monitoring system, the event of no-leak "safety", a leak forecast "warning", and a "hazardous" spill state, respectively. If there is no leak detected, the system is in a “safety” state, and green lights are up. When a small amount of leakage is detected, a system is alerted and the lamp lights turn yellow, but when a large amount of oil leak is detected, the warning signal will be triggered, and the color will glow red. Simultaneously at the monitoring segment, the user will be informed and requested an instant action. For precision sake, there is a chance to change the pressure fall to obtain better results.



(a) (b)

Figure 8. The oil leakage monitoring system is (a) a safe condition and (b) a dangerous condition

The oil concentration is detected by the WSN sensor and according to voltage output, the warning unit, independent control system, and the monitoring unit using Arduino Uno as a microcontroller for the entire system. The data acquired from the gas sensor will be transmitted by the ZigBee to the monitoring system which is presented in LabVIEW GUI. In addition, when the leak happens, the operator can take instant action. However, if no action is taken, the system will stop the oil supply and sets itself to auto shutdown within 10 minutes to prevent further damages.

6. RESULTS AND DISCUSSION

This paper aims to evaluate the feasibility of the pressure sensor based on a wireless sensor network that can be connected to the pipeline. This research introduces a group of trials performed applying the suggested detection technique for leak recognition. A pressure sensor was used with a computer-controlled Arduino Uno to control the inner oil pressure in a tube with simultaneous confirmation of the pressure meter. Two distinct pressure-based leak detection techniques have been explored. The leak detection techniques were founded on hydrostatic responses and stress transient stresses.

Experimental results are supported by an evaluation of the functionality, reliability, and durability of the pressure sensor. In this test, the leakage hole was prepared by drilling a circular (spoil) hole in the center over the pipe cap. The experiment was performed on two models and boreholes were drilled on each end cap with a size of 5 mm and 15.5 mm, as shown in Figure 9.

The size of the leak is determined by the orifice diameters. Initially, a damage-free end cap (reference end cap) was fitted to the conductive joint (ball valve replacement) to simulate a leakage condition. By operating the valve connecting the tube to a 400 kPa oil source, a transient event is created and reinforced in the tube. The transient event was observed with a pressure sensor, and then the experiment was repeated twice with different end caps one after the other. The modified compression files are shown for each of these transients. To guarantee the stability of the pressure sensor and the results, the WSN type pressure sensor has been replaced with a normal pressure sensor and operated under the same conditions. The obtained results are close to the regular pressure sensor used on the project. To measure the pressure profile for this series of experiments, the results of pressure loss and leakage rate are shown in Figure 10. The findings revealed that the wireless sensor was able to identify the pressure drop due to the leakage. This device can be considered an efficient and economical solution for leak detection.

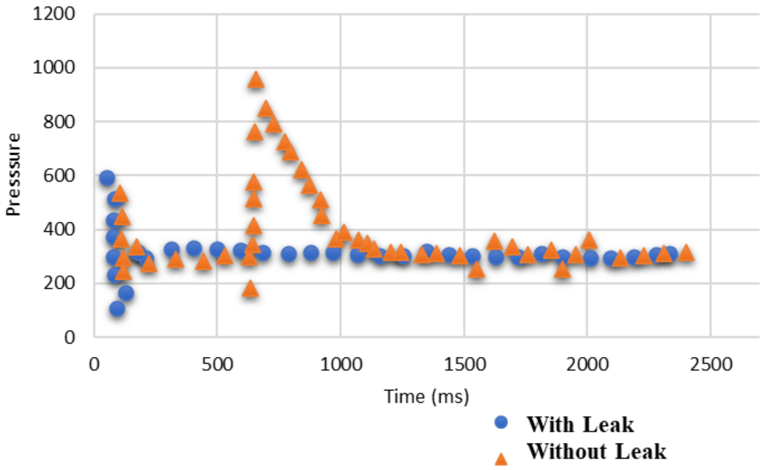


Figure 9. Pressure variation with and without leak

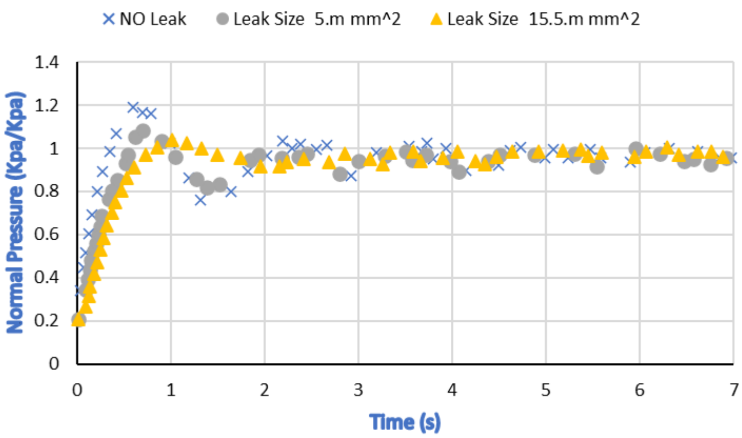


Figure 10. Normalized pressure profile with a various leak size

7. CONCLUSION AND RECOMMENDATION

In this paper, the proposed system is developed to detect leakage and its location in oil pipelines. The leakage monitoring system was developed using the power of rapid computing through a remote sensor network (WSN) to adapt to the conditions prevailing in Iraq. Thus, simulation of pipelines model is achieved using (GUI) without neglecting its real-time operations on the computer. The proposed system describes the new visual LabVIEW approach in a low concentration oil leak detection. The leak is detected with the help of a pressure sensor. Here is a set of conclusions based on the research findings: i) the system works well and can collect data wirelessly with a coverage range of up to 1,000 meters. The coverage area can be increased by using the latest ZigBee unit, ii) when the pressure in a part of the pipeline is reduced below a certain level, the sensors of this system sense this phenomenon remotely and automatically, iii) low cost and scalable, as it was designed by self-effort using university laboratories, iv) it has a low energy consumption as it uses the ZigBee protocol, which has this important advantage, v) able to save the collected data electronically with the ability to programmatically set the parameters of the Arduino Uno controller through the application implemented in the LabVIEW environment, and vi) the system can be used to monitor various applications such as temperature and pressure using appropriate sensors.

In conclusion, the experimental results showed that the leakage is accompanied by a decrease in pressure in which the size of the leak determines the extent of the pressure drop. Therefore, pressure drops or changes are used to locate the leakage sites. The accuracy of leakage sites will be increased by using more field sensors. In the future, we intend to increase the number of sensors to more than four and monitor the temperature simultaneously.

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