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Pipeline Fault & Leakage Diagnosis in Smart Oil and Gas Field using Electrical Capacitance Tomography: A Review

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ABSTRACT

Purpose - Smart Oilfield Technology is promising concept in oil and gas fields worldwide. The common goals are reducing capital, improving total recovery, and improving human and environmental safety. Pipeline networks have been providing the most economical and safest method for transporting crude oil. Nonetheless leaks can cause losses in recovery of the transported hydrocarbon fluids and gasses. Pipeline leaks could turn to pipeline failure in serious cases which is a hazard to human and ecological, and substantial financial loss. The current methods used are exterior part pipeline monitoring, visual method that is done periodically and interior method that determine leakage by calculations from sensor readings. Each of the current methods have weaknesses in determining the actual leakage occurrence. Therefore, the need for a study for a smart and reliable pipeline leak detection is essential. In this study the effectiveness of using a twin plane electrical capacitance tomography (ECT) for oil and gas pipeline leak detection is investigated.

Design/methodology/approach - The pipeline fault and leakage diagnosis are complete with the analysis of the comparative data between the twin ECT pair placed at the upstream and downstream on the pipeline. In this research, a twin plane 16 segmented sensor are mounted as one up-stream sensor and the other as down-stream sensor. The presence of different types of material such as oil and gas concentration will produce different permittivity value for the capacitance of the sensors. The permittivity distribution demonstrates on a sensitivity map throughout the sensing cross-sectional area of the pipeline will provide crisp data for image reconstruction.

Expected Outcome – Sensitivity map is utilized for determining difference of the material composition and concentration in the pipeline from the upstream and downstream sections. The pipeline fault and leakage diagnosis are realized by analysing the changes of data classifying the changes of gasses and liquids concentration from upstream and downstream sensors

Keywords: Pipeline Fault Diagnosis, Smart Oil and Gas Field, Electrical Capacitance Tomography.

1. Introduction

1.1 The need of pipeline failure and leakage monitoring

Pipelines are among the best and most dependable means of hydrocarbon transfer methods. Still, failures in oil pipelines have comprised doing significant human and economic losses. Annually there are hundreds of pipeline failures, leading in contamination, loss of transportation content, deprivation of gas availability, and repair spending [1].

To the highest degree of the failures happen takes a while to be repaired and hence are more severe in terms of business suspension [2]. Checking the reason of failure along a pipeline is to learn what gives rise to the failure hence in next time to come the operators could proceed with immediate actions to disallow or minimize the designated failures (referring to Figure 1). This is the primary reason progressing to a failure analysis that take aim on high importance, and it should thus be executed in a consistent and orderly way with appropriate instruments.

Figure 1. Picture of a pipeline crude oil transportation system with failure example [1]

Industrial facilities and pipelines systems demand compulsory hazard judgement and development of preventive and protective activities. These activities could be improved having consideration of the outcomes of failure analysis. However, operators and companies with industrial installations and pipelines particularly in oil processing, chemical, and petrochemical industries are implicated, there are a total of three primary reasons of failures.

They are namely stress corrosion cracking, internal corrosion, and external corrosion, which are time reliant (referring to Figure 2). Issues that increase the risk of pipeline failure includes the propagation of defects due to fatigue because of fluctuating pressure, corrosion, and erosion of pipelines [3].

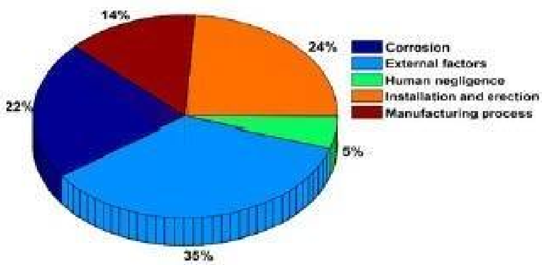


Figure 2. The statistics of the origins of pipeline failure [3]

Once a failure takes place it could initiate related accidents leading in discharge of dangerous stuffs that trigger fires or even explosions potentially wounding people and amplifying the total damage to nearby region. Source from New Straits Times (NST) online news, stated that, in 12April, 2019 an explosion occurred at Refinery and Petrochemical Integrated Development (RAPID) plant, located in Pengerang, Southern Johor, Malaysia (referring to Figure 3). The disaster resulted in human injuries and capital losses cause are from pipeline failure. Failures such as this pipeline explosion could be prevented if failure detection steps are taken as prevention before the incident.

Figure 3. Pipeline explosion at RAPID Pengerang plant (Source from NST).

1.2 Smart Oilfields Technology

Technological solutions called smart oilfields have been implemented in oil and gas industry for almost two decades. The intention is to improve the knowledge of petroleum output operations, and thereby improve the efficiency of processes. The growing trend of real-time plant data acquisition and condition monitoring with comparison of the discontinuity and unstableness of the conventional data measurement and logging technology of intelligent oilfield technology is on-going and constant [4]. It avails to guarantee higher accuracy, keep off the effect of conventional data logging on typical production and guarantee higher efficiency. Consequently, in the term smart or intelligent is related with the user-friendly side of technology that assists the operator in managing with possible issues right away [5]. The main leading problem in the oil and gas industry comprises monitoring of multi-phase flow comprising of gas, oil, and water in pipelines. It is related to difficulties involving submerged instrumentation of the multi-phase flow leads to a big problem in oil transportation [6]. If the intelligent technology can be accomplished concurrently, it is not only holding advantages in decision accuracy, but as well cuts down the workload and operative time of logging and lifting instruments. This will significantly be improving output efficiency and reducing output and production costs. Oil and gas industry frequently comprises a multitude of unidentified losses, particularly on pipe ruptures and leakages. Therefore, discovering even the most minor leakage within a measured tolerance possesses its environmental benefits together with economic aspects. These pipelines and vessels (as can be referred to figure 4) are subjected to numerous relative incidence that is assigned to traffic and surface loads that induce the overstress along the pipes and joints, which may result to leakage, burst and spillage from pipeline [7].

Leakage detection techniques mostly are separated into two primary categories, software-and hardware-based methods. To ward off such threat and sustain safe and reliable pipeline system structure, significant research attempts have been dedicated to carrying out pipeline leakage detection employing various approaches [8].

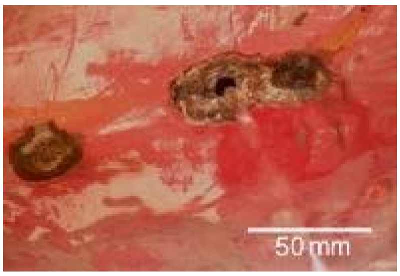


Figure 4. Fault example from a segment of a pipeline induced by punctured hole [2].

2. Current Failure Detection Methods

A wide range of pipeline leakage detection methods was examined and categorised into three groups. The first category includes exterior methods, which entail the use of specially built sensing devices to monitor pipelines' external portions. Vapor Sampling, Capacitive Sensing Measuring, Acoustic Emission Sensors, Fibre Optic Sensors, and Electromagnetic Reflection are some of the methods covered in this lesson. The visual methods of pipeline leakage detection, which include Smart Pigging, Drones, Autonomous Underwater Vehicle (AUV), Remotely Operated Vehicle (ROV), experienced employees, and trained canines, are included in the second class. The third class uses sensors and metrics related to hydrocarbon fluid, such as Negative Pressure Waves, Pressure Point Analysis, and Mass-Volume Balance, to detect leaks inside the building. [3].

2.1 Exterior Based Methods for fault or leakage detection

Primarily, this entails the employment of detection devices, notably for monitoring the pipelines' external portions. These methods can be used to detect anomalies in the pipeline's surroundings as well as the occurrence of leaks. These detection methods are based on physical contact between the sensor probes and the pipeline system structure being monitored, regardless of the operating principles. Vapor Sampling, Capacitive Sensing Measuring, Acoustic Emission Sensors, Fiber Optic Sensors, and Electromagnetic Reflection are examples of these devices [9].

The functional principle, effectiveness and disadvantage of these methods can be referred to example of vapour sampling (referring to figure 5). The effectiveness of vapour sampling technique is referred to the potentiality of detecting minor leakages, unconditional of the flowrate and pressure balance, while carrying out leakage detection in multiphase flow applications. In addition to that, the sensor could resist substantial hydrostatic pressure. Still, among the leading insufficiencies of this method is the reaction or time response. Generally, it needs several hours to days to react to leakages. Hence, pairing a vapour sensor with some other leakage sensing method will offer better reaction time [3].

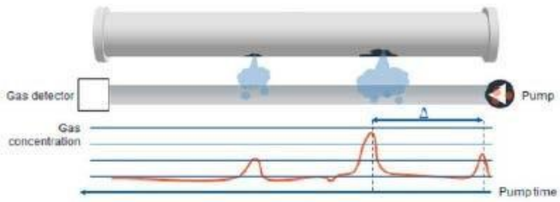


Figure 5. Sensor hose system for pipeline leakage detection [3]

Acoustic Emission detects leaks by detecting inherent signals emitted by a ruptured pipeline. It's easy to set up and use for early detection, as well as being portable and cost-effective. However, it has the flaw of being sensitive to random and environmental noise, prone to false alarms, and unsuitable for minor leaks [10].

Leaks are discovered via fibre optic detection, which recognises temperature variations in the optical attribute of the cable produced by leaks. This approach has the benefit of being unaffected by electromagnetic disturbances, and the optical fibre can function as both a sensing element and a data transmission medium. However, the method's biggest disadvantage is its high implementation cost, as the cable's length is as long as the pipeline itself.

Electromagnetic Reflection measures emitted energy from evaluation of contrasting wavelengths. It can detect leakage position at the pipeline almost with high accuracy. Still, it is inclined to false alarm because it can be affected by terrible weather condition [9].

Capacitive detection method evaluating changes in the dielectric constant of the substance surrounding the sensor. This method is utilised for sensing in non-metallic objects. The disadvantage is that it needs direct contact with the detected substance [3].

2.2 Visual/ Biological Methods for Fault or Leak Detection

Leakage sensing using visual or biological means is similar to the traditional procedure of detecting oil leaks and spills in pipeline environments using Smart Pigging, Drones, Autonomous Underwater Vehicles (AUV), Remotely Operated Vehicles (ROV), experienced workers, and trained dogs [12].

This procedure usually entails trained employees walking beside pipes and inspecting the area around them for abnormalities. Visual inspection or smelling the scent emanating from a damaged pipeline segment are used by expert observers to detect and identify leaks. Similarly, the noise or vibrations produced when oil seeps from a fracture or pierced location are important in detecting and locating pipeline problems. To qualified and expert employees, both dogs and clever pigging work in the same way [13].

When visibility is good, the pig is periodically supplied with sensors and data collecting devices such as an optical camera with a long detection range. Unfortunately, these methods have certain flaws as well. For example, the detection time is based on the frequency of inspections, which are normally performed once every three weeks. Because the inspection isn't done in real time, there's a chance that a serious pipeline collapse will go unnoticed, especially if there's a long period of time between inspections [13].

Through the implementation of intelligent control equipment, autonomous underwater vehicles (AUVs) in subsea pipeline inspection monitoring have reduced the extent of trained staff participation in remote-controlled vehicles, lowering the risk of human catastrophic accident. While the theory of operation of AUVs is similar to that of ROVs, just a few skilled operators are required for supervisory command of AUVs. The use of unmanned vehicles (as shown in Figure 6) for pipeline defect detection has the benefit of acting as a remote operating system, making it suitable for inspection in distant and dangerous environments. Unmanned vehicles provide a number of advantages, including cheap maintenance costs and increased operational safety. Unfortunately, these systems have limitations as well, such as the high initial cost of purchasing or renting an AUV/ROV. Bad weather conditions, including as strong winds and thick clouds, as well as other climatological phenomena, might further impede the functioning of these vehicles [12].

Figure 6. Different kinds of AUVs and ROVs [10]

2.3 Interior or Computational Methods for Fault or Leak Detection

The Negative Pressure Wave technique is an example of this method (referring to Figure 7). When a leak occurs suddenly somewhere in the pipeline, it causes a transient pressure decrease at the leakage location, resulting in a negative pressure wave. The sensors at both ends of the leakage location can determine the leakage position based on the pressure signal shift and the time difference between the leakage's negative pressure wave and the upstream and downstream waves [3]. In this case, where the micro slow leaking is ineffective, an altered algorithm is now advised. Simultaneously, the wavelet transform technology is used to remove the signal of a brief negative pressure wave, and the feature spots of the measurement spot signal are identified and stored at both ends, thus boosting the process' sensing accuracy [14]. There are two placement strategies based on this concept, one of which uses a differential algorithm to quickly grasp the waveform properties. and a positioning approach based on the correlation function's peak point. The precision of leakage position is increased by combining these two procedures. Negative pressure wave signals are detected using a variety of pressure sensors. The true reason for negative pressure waves is discovered by registering the sequence of negative pressure waves using two groups of pressure sensors that fit into this set up. The disadvantage of this system is that in a batch operation when valves are opened and closed at the same time, transient states may occur, resulting in a period that might easily lead to a false alarm [13].

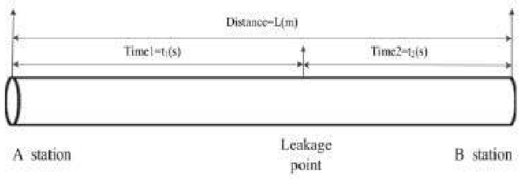


Figure 7. Negative pressure wave monitoring system [3]

The Mass-Volume Balance is another example. For leak detection, it uses the difference in fluid mass-volume between upstream and downstream. It's inexpensive, portable, clear, and unaffected by background noise. Even so, it is relevant for leakage localisation but not for detecting leak size [15].

Finally, the Pressure Point Analysis approach uses numerous sensors to detect pressure fluctuations at various sites throughout the pipeline system. Appropriate for submerged water environments, low temperature regions, and working under a variety of flow conditions. The key problem is that in batch procedures where valves are opened and closed at the same time, leakage monitoring is difficult [14].

3. Suitability of ECT Portable Sensor Design for Pipeline Fault or Leak Detection

This paper targets to investigate the employment of a portable sensor design in an Electrical Capacitance Tomography (ECT) system. Previously Capacitive Sensor is used in pipeline failure detection with the principal measure changes of capacitance based on permittivity of detected material. To extend the usage of capacitive sensors, ECT is used as a combination of exterior sensor by using Capacitance Sensing with the Computational/Internal Method of using algorithm for image reconstruction.

The advantage of ECT is that it is non-invasion and non-intrusion technique and one of the measurement procedures that is dependable, and easy to be utilized. For flow tomographic imaging, ECT sensors are also placed or mounted on the pipeline or vessel. ECT is also commonly utilized in the oil and gas industry, particularly for measuring multiphase flow [11, 12].

ECT is not just for imaging mixtures in process equipment; it can also be used to measure component concentration profiles, and in some situations, it's even being utilized to investigate the boundaries and phase sizes within tanks and pipelines [13].

Using the capacitor fundamental principle, one electrode will operate as an excitation electrode as it is provided with a sine-wave signal. At that point, the remaining electrodes are connected to the artificial earth potential and serve as a detector. The capacitance of the dielectric will be measured and transferred to the measurement circuit during the procedure. Each electrode will take their turn as the excitation electrode until the cycle is completed.

The main idea behind ECT is to use numerous electrodes to record capacitance changes and then upload the data to a computer for image reconstruction based on permittivity distribution [14]. Essentially, it depicts the distribution or changes in dielectric characteristics of materials in the pipelines under investigation.

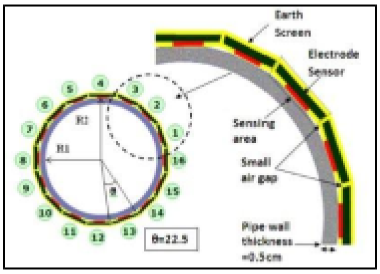
The sensors, measurement circuits, and image reconstruction algorithm are the three main components. The sensor array should be able to take multiple, localized measurements throughout the research region. This is accomplished by carefully placing the electrodes around the item. Depending on the application, the number of electrodes in a set of sensors might range from 8 to 16 electrodes [15].

3.1 The sensor arrays

The advantage of a portable ECT system is the ability of the sensors to be adjusted to the subject's geometry. In most cases, traditional ECT sensors are mounted and fixed on the pipeline, which makes any future process installation complicated. A study was conducted on a small parallel ECT sensor that would provide certain advantages in visualizing any target with specific geometry. This is a common aspect of a portable ECT system that requires a unique measurement set design to measure a certain geometry [16].

A segmented portable ECT system has been designed to address the issue whereby the sensor module works independently, with the number of sensor modules deployed based on the size of the pipes. The segmented ECT sensors mounted around an acrylic pipe referring to Figure 8. To ensure that the electric field is spread evenly over the target, the cross section of the pipeline must be divided evenly into 16 sectors with the angle 22.5° for the 16 segmented sensors [15].

8(a) Portable Segmented ECT



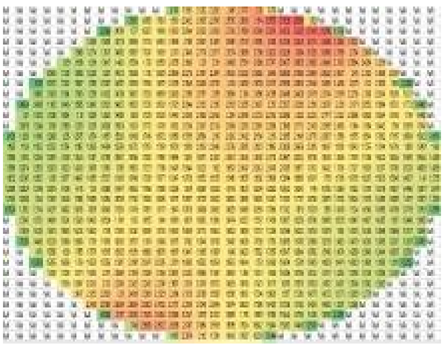
8(b) Cross-sectional view of 16-segmented electrodes

Figure 8. Complete ECT sensing module

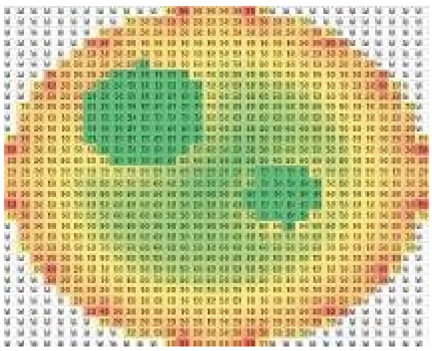
3.2 The measurement circuit (Electrical Potential Sensitivity Map)

The sensitivity distribution of an ECT system is a Jacobian Matrix that provides the sensitivity map for each electrode pair measurement. To acquire the permittivity distribution of an image reconstructed, the presence of the sensitivity distribution of the ECT sensing region is required. The sensitivity distribution is basically the sensor response map to a small single patch of high permittivity material in a low permittivity background that is distributed throughout the sensing area [17].

The absolute capacitance obtained from the simulation is converted into a 32x32 matrix to obtain the sensitivity distribution. This will generate a sensitivity map, and the phantom permittivity will then be multiplied. The capacitance sensitivity matrix recorded between electrodes 1 and 2 is shown in Figure 8(b) [18]. When the pipeline contains a similar medium, such as air in this example, the Electrical Potential Sensitivity Map displays the electrical potential in each pixel of the ECT shape are shown in Figure 9 (a).



9 (a) Sensitivity Map without phantom object



9 (b) Sensitivity Map with phantom object included

Figure 9 Electrical Potential Sensitivity Map [18]

3.3 The image reconstruction

The permittivity of the medium or substance in the pipe influences the capacitance (C) value. As a result, the higher the permittivity in relation to the electric field, the higher the value of the distribution electric displace displacement field normalization for each pixel in the sensitivity map [18].

As a result, the material or medium inside the pipe may be identified, and the formation of the phantom that represents the foreign medium or substance can be observed are shown in Figure 10 (b). After the results are obtained, the image is reconstructed to reveal the phantom (foreign material or medium) by utilizing the standard deviation equation for each value obtained in each pixel. The signal will be detected by the measuring circuit, which will condition it, gather data, and convert it to a digital signal before sending it to the image reconstruction processor (referring to Figure 10) [19]. There are numerous image reconstruction techniques, the most prevalent of which is the linear back projection technique [20,21].

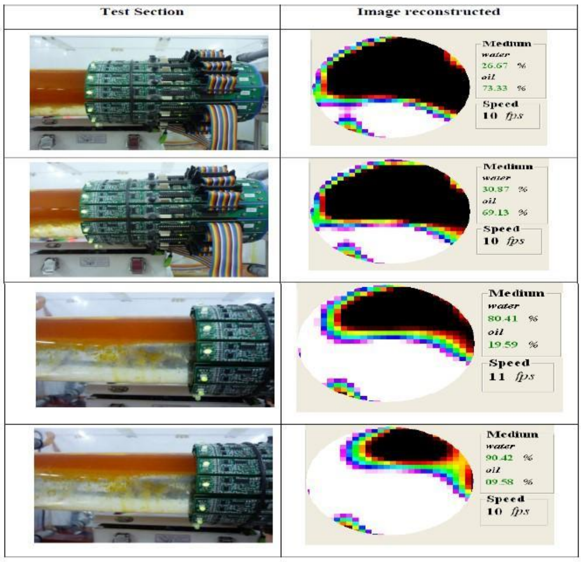


Figure 10. Reconstructed image of horizontal oil–water flow concentration [19]

4. Twin-Plane Segmented ECT System as The Complete Fault and Leakage Diagnosis System

The application of twin-plane tomographic systems has prospective to provide significant data in multiphase flows without the demand the phase flow separation [22, 23]. Previously it is used as a method for evaluating the concentration and the velocity distribution of multiphase flow [14]. It is by combining of tomography and cross-correlation technique provides a chance to measure the velocity profile of a multiphase flow. For this study, the concept of tomography images from upstream and downstream are used but with the extend of studying the differences to provide data of dissimilarity. The dissimilarity of the tomographic images from the upstream and downstream will be evaluated in finding the fault or leakage occurring in the pipeline system.

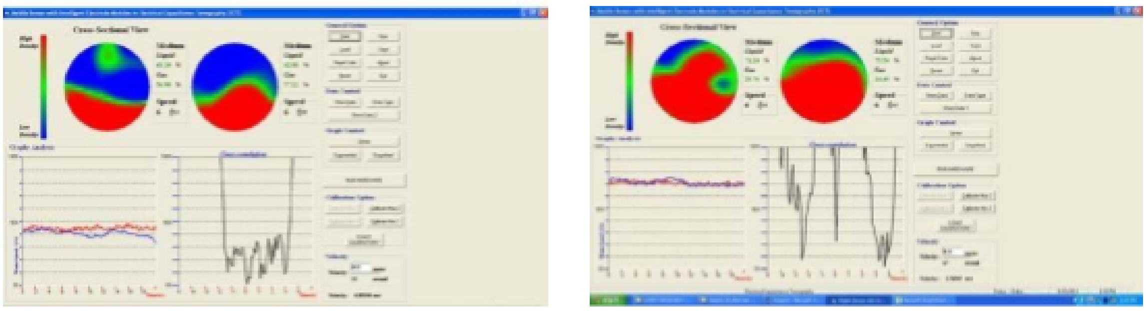
A twin-plane of segmented ECT sensor electrodes is produced to evaluate the image of the material concentration where two sets of sensor electrodes are mounted on a horizontal pipeline (referring to Figure 11) [24]. The arrangement of the sensors is to be known as the upstream sensor for left-side sensor position and the downstream sensor for the rightside of the sensor position.

The configuration of the system is to be flexible and portable whereby independent functionality of each sensor are anticipated. It can be employed along pipelines with dissimilar diameter and dissimilar amount of electrode sensors without the necessitate to redesign the system [25].

The pipeline on both upstream and downstream plane are set up with attachment of a set of 16 electrode sensor modules symmetrically surrounding it with hexadecanol form. The focus is on the ECT sensor is arrangement which is placed horizontally. The ECT sensor is portable and built up by utilising particularly configured Printed Circuit Board (PCB).

Figure11. A twin-plane segmented ECT sensor with 16 portable electrodes [24]

The result of testing the upstream and downstream sensor arrangements produces tomographic images as in Figure 12. Reconstructed image tomogram for liquid volumes of 15 LPM and 25 LPM produces images almost similar for both the upstream and downstream whenever the pipeline has no fault occurrence [24]. Therefore, by employing this result, the system hypothetically to be suitable to be explored for pipeline fault and leakage diagnosis.



12 (a) Liquid flow velocity 0.029m/s

12 (b) Liquid flow velocity 0.036m/s

Figure12. Reconstructed image tomogram for liquid volumes of (a) 15 LPM and (b) 25 LPM [24].

4.1 Testing Faults Conditions and Acquiring Real-time Data from Sensors.

A pipeline system is installed with different sets of sections to simulate leak faults such cracks, ruptures, and loose joints leakage. The pipeline will also be installed with other industrial process sensors which are flow, pressure, and temperature for data evaluation during faulty simulation.

The ECT pair is placed on opposite ends of a pipeline section, at the upstream and another at the downstream flow of the test material flowing in the pipeline. The pipeline could be several kilometers long in actual. For this experiment, the pipeline is set to be a few meters long. The difference in data from ECT at upstream and ECT at downstream is acquired in real-time and use as input for diagnosis and stored for reference.

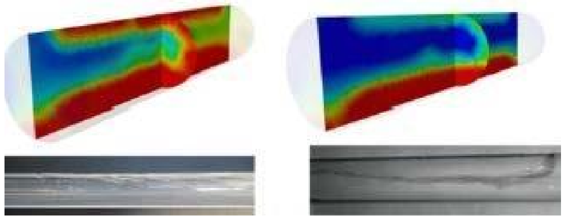


Figure 13. Illustration of the expected result detection material composition and concentration when fault occurs [26].

Whatever irregularities could supply a useful data about their current state and provide uninterrupted and real-time monitoring. By employing this representation, liquid and air region can be classified according. The boundaries at values at sensitivity map in between 0 and 1 can be assigned to be between value (number) between 0 and 1which can be associated with almost false and half true. It is therefore the humanlike reasoning can be utilized for the output.

Therefore, the fault in term of leaks could be understandable by operator without needed expert experience to perform immediate action when need of fast response.

4.2 The Continuous Monitoring and Diagnosing

Cloud computing has emerged as one of the most promising technologies in medical imaging in recent years, as it provides a solution for long-term medical image archiving [24]. Normally, the system controls the entire process, and the human operator will only assist in an emergency or in the event of an unexpected event.

Cloud computing can be applied specifically for the ECT portable system for raw data management, image processing, and analysis. The system may be required to gather data from many sensing and control units to prepare data for the human operator so that the entire system may be readily monitored.

5. Conclusion

Smart oilfield technology is a good impact to the nation for contribution of society, industry and environment. Society could benefit in terms of reducing hazard to people in the case of fatal disaster from pipeline failures. Furthermore, in the form of manpower, worker exposure to harsh environment could be minimize as the pipeline inspection frequency is minimize by having automated fault diagnosis system. Environment and economy are also positively affected by this technology as leaks or spills could be prevented.

To summarize, each technique has advantages and disadvantages. Most interior systems, for example, are sensitive to minor leaks, especially if the leakage point is close to the sensing device, but they are more prone to false alarms because they are easily affected by background noise. Therefore, this research aims combining the Capacitive Sensing from the exterior based leakage detection method with the Interior method of ECT sensitivity map data evaluation method.

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