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Initial Study of Invasive Approach of Electrical Capacitance Tomography for Identifying Non-Conducting Medium in Steel Pipe Application

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Abstract: The paper aims to investigate the possibility of an invasive method for electrical capacitance tomography system for steel pipe application. This work presents the development process for modeling an ECT (Electrical Capacitance Tomography) sensor using COMSOL Multiphysics. COMSOL Multiphysics software is implemented as the main tool to model the ECT system. The 12 electrodes are modeled in 2-dimensional and it is based on the invasive approach. The ECT system is developed to obtain the electrical potential distribution between electrodes when an electric field is applied. Besides, it also obtains the permittivity distribution inside the closed pipe. This invasive approach is applied for the steel pipe that cannot be used with common ECT. Several positions of bubble air as the obstacle in the oil medium are tested. As a result, the sensor readings performance inside the region of interest is analyzed. Simultaneously, the tomograms are also obtained and analyzed using MATLAB software. A linear back-projection algorithm is implemented to reconstruct the image of the region of interest. Thus, the possibility of the ECT system applied for steel pipe can be observed and compared when there is a change of readings between the full oil and the existing obstacle inside the steel pipe. Besides, the tomograms for each condition tested can be observed. In short, the invasive approach for ECT is seen to be possible to apply for oil-gas application in steel pipe. The LBP algorithm with the average MSSIM value around 0.3 was able to detect the oil-gas regime inside the steel pipe.

Keywords: ECT, Invasive, non-conducting medium, steel application

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1. INTRODUCTION

Electrical capacitance tomography (ECT) is an image analysis method that had been developed for industrial applications. A fundamental principle of ECT is to calculate a variation in permittivity due to a different material or different material distribution inside an ECT system. ECT sensor consisting of numerous electrodes, typically 6, 8, 12, or 16 that are typically installed in circular conducting pipe or insulated pipe around the external or internal periphery [1] – [3].

ECT is used in industrial applications for two or three-phase measurement flow parameters. A high potential for industrial application is the invasive approach of electric capacitance tomography. The ECT study is currently based only on the insulation wall vessels and pipelines at present [4]. However, in the industrial area, there are mostly use steel pipelines and vessels. Hence, the common ECT approach, using a non-invasive approach cannot be applied to detect oil and gas regimes in steel pipe applications. It is due to the signal will only propagate around the steel pipe and cannot penetrate the pipe. Therefore, this paper develops an ECT system for steel pipe application based on an invasive approach that requires the use of an insulated pad between the electrodes and metal wall inside the vessel. The insulated pad is applied so that it can avoid a grounding effect.

2. BASIC PRINCIPLES OF ECT

The basic principle of an ECT system is to measure the changes in capacitance from the multi-electrode sensor and then reconstruct a permittivity distribution, using the measured capacitance data. In these applications, the sensors usually consist of two electrode plates and the capacitance [1]. The requirement for the electrical capacitance tomographic imaging is that multiple electrodes should be arranged around the boundary of the region and the capacitance between all the combination pairs of the electrodes should be measured to perform a 'body scan' of the imaging volume. It is developed to image industrial processes containing dielectric materials, for example, gas/oil flows in oil pipelines, gas/solid flows in pneumatic conveyors, and fluidization processes in fluidized beds.

ECT is most successful when applied to materials such as oils, plastics, dry powders and under favourable circumstances pure water, all of which have low electrical conductivity [1].

A complete cycle for a common ECT system measurement is started with the first channel (named as electrode 1) act as the excitation electrode. When the transmitter is supplied with a sine wave, all other channels will set to the ground and act as receivers and receive the capacitor values. It corresponds to the dielectric between the transmitter and each the receiver [1]. For a complete measurement cycle, all channels will become transmitter and receiver.

However, this common ECT measurement cannot be applied to a steel pipe. It is due to the interaction of the metal electrode and the steel pipe itself. If the non-invasive approach is applied, and due to both media are metal, the signal will only tend to propagate in the circumference of the steel pipe without penetrating through the pipe. Consequently, the electrical field propagation inside the steel pipe cannot be observed and analyzed. Besides, the measurement of the ECT system in steel pipe is similar to the conducting boundary method in the ERT system. The excitation channel will be set as the source signal, the receiver channels remain floating, and the body of the steel pipe is set as ground. The difference if compared to the conducting boundary in ERT is in terms of the principle. The ERT is used to reconstruct the image based on electrical conductivity distribution meanwhile the ECT is getting the tomogram based on the electrical permittivity distribution.

The mathematical equation of the ECT system is based on the electrostatic field. The relationship between the spatial distribution of the permittivity and the measured capacitances is shown in Ref. [5], which can be derived from Maxwell's equation as in Equation (1). Gauss's Law expresses the dielectric flux density, D.

$$\nabla \cdot D = \rho_v \tag{1}$$

The ρ_v stands for the volume charge density, while ∇ is the divergence operator. In ECT system, only one electrode is excited at a time and the rest of electrodes will be receiver, this total electric flux over all the electrode surfaces can be calculated as zero, thus the volume charge density is also zero, given that:

$$D = \varepsilon E \tag{2}$$

$$E = -\nabla\varphi \tag{3}$$

With ∇ is the gradient operator so we have

$$D = -\varepsilon\nabla\varphi \tag{4}$$

where ε is the spatial permittivity distribution. E is the electric field intensity and φ is the electric field potential distribution within the sensor. As in Equation (4) into Equation (1) giving Poisson's equation.

$$\nabla \cdot \left(\varepsilon(x,y) \cdot \nabla\varphi(x,y)\right) = 0 \tag{5}$$

For a two-dimension case that include x and y axis case, gives the $\varepsilon(x,y)$, is the relative permittivity distribution in two dimension with the boundary conditions, $\varphi = V_C$ for first electrode and $\varphi = 0$ for the remaining electrodes.

3. METHODOLOGY

This works are concentrates on the design and simulate the ECT system with COMSOL Multiphysics for steel pipe Thus, the internal electrodes must be selected instead of external electrodes. Figure 1, shows an ECT measuring flow system where the ECT sensor consists of twelve electrodes attached equidistantly along the periphery of the conducting pipe vessel. The 12 segmented electrodes are labeled from 1 to 12, and the measurement protocol in the sensing electronics first measures the inter-electrode capacitance between electrodes one and two, then between one and three, and up to one and k, where k = 12 in this case. Then, the capacitances between electrodes two and three, and up to two and k are measured. The measurements remain until all the inter-electrode capacitances are measured.

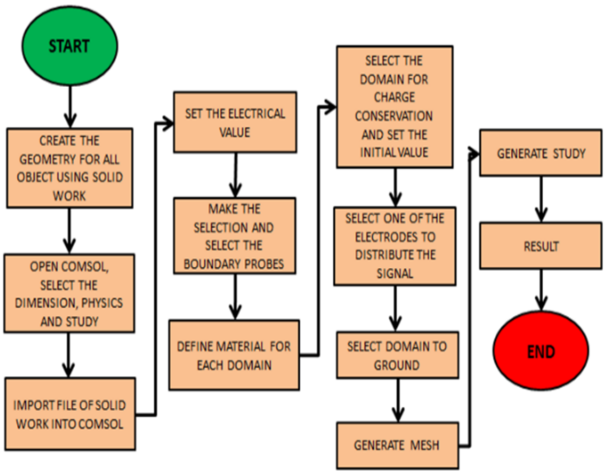


Figure 1. Basic flow process inn COMSOL Multiphysics

The 2-Dimensional of the 12 electrodes ECT is illustrated in Figure 2. The detail of the parameter used can be found in Table 1.

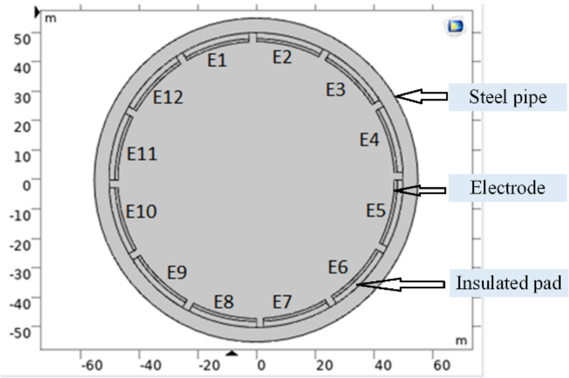


Figure 2. Geometry of 12 electrodes of ECT

Table 1. The detail parameters used

Domain	Parameter	Value
Pipe	Outer diameter pipe	110mm
	Inner diameter pipe	100mm
	Thickness of pipe	5mm
	Material	Structural steel
	Relative Permittivity	1
Electrode	Number of electrode	12
	Stretch angle of electrode	27°
	Thickness of electrode	1mm
	Material	Gold
	Relative Permittivity	1
Insulator pad	Number of insulator	12
	Stretch angle of insulator	27°
	Thickness of insulator	2mm
	Material	FR4
	Relative Permittivity	4.5
Oil	Relative Permittivity	3.25
Air	Relative Permittivity	1

The electrical signal was set by 25V for every injection at excitation signal at each of the boundary channels. The sine wave with 500 kHz excitation signal is good for the circuit to achieve linearity and stability but this paper only focuses on the simulation part so it was decided to use only dc voltage to get a positive value reading and to avoid the reading value too small. Later, the mesh of ECT was generated. The extra finer mesh was applied in this paper. Later, the sensing readings performance was analyzed and the image reconstruction with the different position was obtained. A linear back-projection algorithm as in Ref. [6] - [7] was applied in this paper to test the capability of the invasive approach of ECT to obtain the tomograms. The 144 x144 pixels were implemented in this paper. The sensitivity distribution was generated from COMSOL Multiphysics and exported into MATLAB software. Also, the efficiency of the tomograms is further investigated using multi-scale structural similarity (MSSIM) as in Ref. [8]. The MSSIM will give a result between 0 and 1. If the value is near 1, it means that the image obtained is closer to the reference image.

4. RESULTS AND DISCUSSION

The measurement of the simulation which was oil and air bubble were conducted in this paper. In the first part of the simulation, the homogenous (homo) and non-homogenous (non-homo) of the subject were tested. The homogenous means that the pipe is filled with oil only and the non-homogenous is referring to the existence of an air bubble with a radius of 10 mm in front of electrode 2, E2. Based on Figure 3, it can be observed that the value of potential difference at R1, R2, R3, R4, R6, and R7 were decreased because the presence of the air bubble was blocking the path of electrical field distribution from excited to electrode to the R1, R2, R3, R4, R6, and R7. Hence, it reduces the signal that can be received by the corresponding receivers.

Besides, Figure 4 shows the streamlines of the ECT system when channel 1 was set as excitation channel and others as the receiver. The streamlines are representing the electrical field propagation inside the region of interest. It was obtained to observe the soft field behaviour of the electrical tomography. Based on Figure 4 (a) the streamline was in a curving line which emits the soft field behaviour of electrical tomography. But, it became distorted with the existence of the obstacle (see Figure 4(b)) inside the line. It is due to the different electrical permittivity between gas and oil. So, when the electrical field propagates from oil to gas or vice versa, it causes the signal to become distorted.

The simulation was continued with image reconstruction by using MATLAB software. The same size of a bubble with 3 different positions was tested. The result was shown in Figure 5. Based on Figure 5 and Table 2, it was proven that LBP was able to generate a tomogram with distinguishing positions of obstacles. The smearing effect occurred in each of the tomograms obtained due to the drawback of the LBP algorithm [9]. However, the ECT system was still able to detect the different locations of the obstacle inside the pipe. Furthermore, the images reconstructed were further analyzed by using MSSIM. Based on Table 2, the MSSIM value gave around 0.3. It is due to the LBP algorithm that produces the smearing effect as stated previously. Moreover, it can be observed that the top right image had the lowest value of MSSIM compared to other positions because its position was a little bit further from the electrode. It is because the higher the distance between the obstacle and the sensor, the less was the performance of the tomogram to capture the exact position of the obstacle.

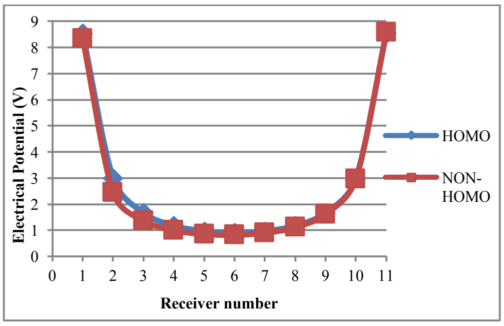
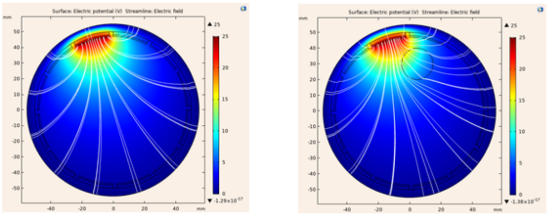


Figure 3. Comparison between homo versus non-homo



(a) (b)

Figure 4. Streamlines between homogenous

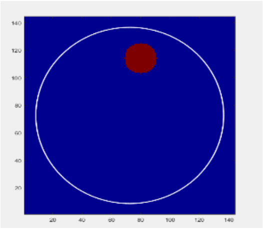
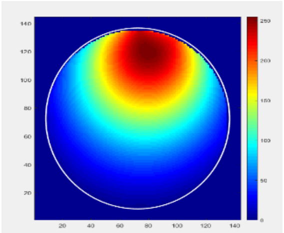
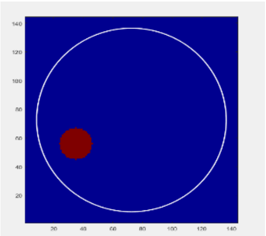
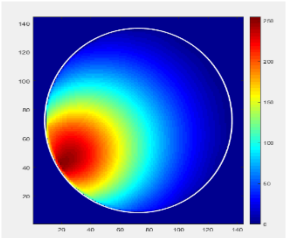
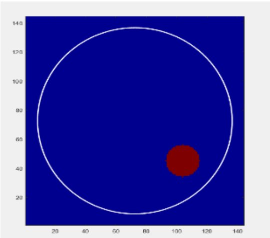
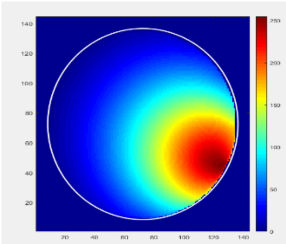
Reference image	Tomogram
Top right 	
Bottom left 	
Bottom right 	

Figure 5. Tomogram for 10mm radius bubble at 3 different positions

Table 2. MSSIM value for 10mm radius bubble at 3 different positions

Position	MSSIM value
Top right	0.2758
Bottom left	0.2844
Bottom right	0.2826

5. CONCLUSION

In short, the initial study of invasive approach of ECT system for steel pipe application was seem able to detect the non-conducting medium (oil-gas) in the steel pipe. Based on tomograms obtained, the ECT system was able to detect the position of the obstacle. However, a further investigation is needed to verify the capability of the ECT system. The future focus of this paper is to test by using real hardware and compare the result with the simulation

In short, the initial study of the invasive approach of ECT system for steel pipe application seemed able to detect the non-conducting medium (oil-gas) in the steel pipe. Based on tomograms obtained, the ECT system was able to detect the position of the obstacle. However, further investigation is needed to verify the capability of the ECT system. The future focus of this paper is to test by using real hardware and compare the result with the simulation results. The variety of mediums tested such as the different sizes of obstacle and medium of non-conducting medium will also be considered.

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REFERENCES

[1] R. A. Rahim, *Electrical Capacitance Tomography: Principles, Techniques and Applications*. Universiti Teknologi Malaysia, 2011.

[2] N. A. A. Rahman *et al.*, "A review on electrical capacitance tomography sensor development," *Jurnal Teknologi*, vol. 73, no. 3, pp. 35–41, 2015.

[3] W. Q. Yang, M. S. Beck, and M. Byars, "Electrical Capacitance Tomography 舒 from Design to Applications," *Measurement and Control*, vol. 28, no. 9, pp. 261–266, 1995.

[4] W. Tian, J. Sun, M. F. Ramli, J. Wang, and W. Yang, "An Electrical Capacitance Tomography Sensor With Variable Diameter," *IEEE Sensors Journal*, vol. 17, no. 7, pp. 2089–2099, 2017.

[5] E. J. Mohamad *et al.*, "Sensor modeling for portable Electrical Capacitance Tomography system using simulation by COMSOL Multiphysics," *International Journal of Innovative Computing, Information and Control*, vol. 8, no. 10 B, pp. 6999–7016, 2012.

[6] Y. A. Wahab *et al.*, "Image reconstruction for solid profile measurement in ERT using non-invasive approach," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 15, no. 4, pp. 1554–1564, 2017.

[7] M. H. F. Rahiman, R. A. Rahim, H. A. Rahim, S. Z. M. Muji, and E. J. Mohamad, "Ultrasonic tomography - image reconstruction algorithms," *International Journal of Innovative Computing, Information and Control*, vol. 8, no. 1 B, pp. 527–538, 2012.

[8] Y. A. Wahab *et al.*, "Image reconstruction for liquid-gas regime identification based on multiple excitation sources in electrical resistance tomography system," *IOP Conference Series: Materials Science and Engineering*, vol. 705, no. 1, 2019.

[9] S. Ridzuan Aw *et al.*, "Investigation on the Effect of Varying Bubble Size and Location in Electrical Resistance Tomography Using Conducting Boundary Strategy," in *Proceedings of the 1st International Conference on Electronics, Biomedical Engineering, and Health Informatics*, pp. 681–694, 2021.