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Electric Potential Profile Study for Electrical Capacitance Volume Tomography

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ABSTRACT

Electrical Capacitance Volume Tomography (ECVT) is a non-invasive 3D imaging technique mainly applied to multiphase flows. As soft field sensor, ECVT suffers the low-resolution image reconstruction especially at the center of the pipe. This paper discusses simulation studies of the electric potential distribution at the center of the pipe for three plane ECVT system. The result shows that the adjacent dual excitation method in the same plane able to produce higher electrical potential at the centre of the pipe compared to other electrode and excitation configurations. This condition gives more sensitivity in the middle of the pipe and at the pipe wall which can improve the quality of image reconstruction to be applied in experimental setup.

Keywords: Electrical Capacitance Volume Tomography, electrical potential profile

1. Introduction

Earlier research shows that the Electrical Capacitance Tomography (ECT) method is used to visualize the flow (image reconstruction) using single-plane electrodes that create a 2D image of the respective flow or phase. The main objective of the capacitance measurement method is to obtain information on the contents of pipes, based on the measurement of variations in the dielectric properties of the material within the pipe[1]. ECT applications have evolved from the use of one plane electrode on more than two planes for velocity profiling [2], [3] and 3D imaging techniques [4]. Sun *et. al.* (2015) attempted to reconstruct 3D image reconstruction using one planar sensor. The experimental results indicated that the optimum in-depth detection is limited up to 65% of the length of the sensor array [5]. Generally, the aim for volumetric imaging is to obtain more accurate flow information in a closed pipe in term of 3D images. in addition, the single plane electrode sometimes does not reflect the actual situation in the pipe where a possible reaction or disposition occurs at different areas where the electrode is installed. This could lead to incorrect assumptions about the actual flow behavior. In general, ECT and ECVT systems are studied by breaking down the system into its three basic components: (1) sensors array, (2) data processing hardware and (3) image reconstruction algorithm as shown in figure 1. Both of the systems also share the same benefits i.e. non-intrusive and non-invasive measurement, cost effective, and fast response [6].

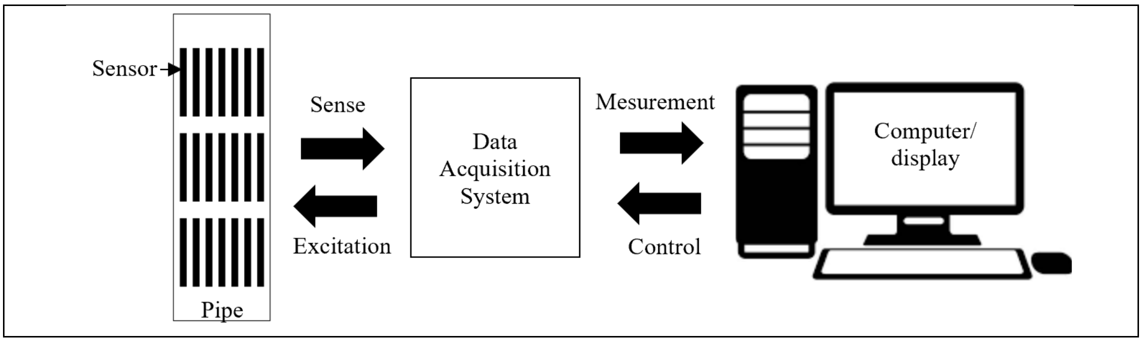


Figure. 1. Basic component of ECVT system

2. Electrical Capacitance Volume Tomography (ECVT)

ECVT was first developed in The Ohio State University in 2009 [7] and it was reported to be a suitable method to be used for industrial applications and multi-phase flow analysis. ECVT can be applied to vessels of various sizes [8] and has been used to understand the condition of the side injection effects with various injection flowrate [9], monitor the amount of fluid in the tank in a microgravity environment [10] and observe the water infiltration by using a small soil column [11].

Although ECVT application is a promising technique, it has shortcomings in terms of producing ill-posed and ill-condition image reconstruction. This is related to the effect of the soft-field sensor where the sensitivity depends on the position of the electrode and the medium in the pipe.[12]. There have been many improvements that have been carried out for the purpose of enhancing the image reconstruction, including improvements to hardware including sensors[13], circuits [14] and optimization of data acquisition system design [8]. Image reconstruction algorithm is one of the factors in getting a good image for capacitance measurement. Many improvements have been made to the image reconstruction algorithm as well. The algorithm is divided into two main categories: non-iterative and iterative algorithms. For non-iterative, the most common and easy-to-use algorithm is Linear Back Projection (LBP) although it produces less than satisfactory images [15]. It is also widely used as a base or comparison to other algorithms. Singular value decomposition (SVD) considers error in measurement and Tikhonov regulation managed to solve ill-posed inverse problem. Landweber iteration and thresholding of Total Variation are examples for iterative algorithms. Iterative algorithm works by obtaining an estimated of the unknown permittivity from the capacitance data (inverse problem) [16].

3. Multiple Excitation Method

Another scope of study to enhance the image reconstruction is to increase the number of excited electrodes simultaneously. The main purpose of multiple excitations is to increase the electrical potential distribution in the pipe which can ultimately improve the quality of image reconstruction [16]. This method is an applicable and relevant way of controlling the modification for electrical signals by regulating the electrode's switching. For 3D capacitance measurement, the electric potential of capacitance measurement can be calculated by solving Poisson equation:

$$\nabla \cdot (\varepsilon(x,y,z)\ \phi(x,y,z)) = -\rho(x,y,z) \tag{1}$$

where $\varepsilon(x,y,z)$ is the permittivity distribution, $\phi(x,y,z)$ indicates the electrical potential distribution and $\rho(x,y,z)$ is the charge distribution, which is the source of the electric field. The equation 1 is a linear equation of the electrical potential distribution $\phi(x,y,z)$. If there is no charge inside the pipeline, the inner potential distribution can be derived as follows.

$$\nabla \cdot (\varepsilon_0 \varepsilon_r(x,y,z)\ \nabla\phi(x,y,z)) = 0 \tag{2}$$

where ε_0 is the permiitivity constant of free space, $\varepsilon_r$is the relative permittivity of medium inside the pipe and ∇ is the gradient operator. The boundary condition of the system is Dirichlet distribution. The voltage setting is V for excited electrode i $(\phi(x,y,z) = V)$ and other electrodes are kept to zero or grounded $(\phi(x,y,z)) = 0)$. The charge sensed by electrode detection can be determined by applying Gauss law using the following equation.

$$\mathrm{Q} = \oint_{\Gamma} \varepsilon(x,y,z)\phi(x,y,z).nds \tag{3}$$

where Γ is the closed curve surrounding the receiver's electrodes and n is the normal vector unit along Γ. By suing the charge Q at each receiver electrodes, the capacitance can be derived as.

$$C = \frac{Q_{ij}}{\Delta V_{ij}} \tag{4}$$

where ΔV_{ij} is the electrical potential difference between the transmitter and receiver electrode (electrode i and j). The multiple excitations method is also known as Protocol order in ECT, for example Protocol 2 refers when two electrodes are excited simultaneously, and Protocol 3 is when there are three electrodes excited at one time. The independent measurement (M) can be calculated as

$$N = \frac{N - (2P - 1)}{2} \tag{5}$$

with N is the number of electrodes, and P is the Protocol excitation.

From the previous studies, the multiple excitation method able to enhanced the sensitivity in central area of the region of the inspection [17] and provide better distribution uniformity of electrical field in . the entire pipe region compared to single excitation [18]. Yang et. al. (2017) [19] indicated that the sensing characteristics improved significantly, allowed to lower the burden of measurement and produced better tomographic images. The multiple excitation method able to speed up [20] the data retrieval process by lessening the number of extraction data from the sensor. This method is performed with no lapping sequence between the electrodes. There are also several studies conducted for electrical volume capacitance tomography (ECVT). The electrodes arrangement is using several planes of electrodes which able to reconstruct 3D images. The multiple excitation sequencing involving rotational of excitation electrodes from different planes. The results also indicates enhanced resolution and stability in the imaging compared to single excitation method [21][22].

This paper focuses on comparison between single and dual excitation in the same plane as well as different planes. The simulation of electrical potential distribution at the center of the pipe based on single and dual excitation method for three-plane ECVT system are discussed.

4. ECVT Simulation

The simulation utilizes multi-physics finite element analysis software COMSOL Multiphysics simulation of the three-dimensional capacitance measurement. COMSOL Multiphysics is a finite-element simulation program used to solve a broad range of partial differential equations (PDE) ranging from acoustics to fluid flow applications. The software also allows users to set different types of domains in the region of interest with customizable setting parameters and user-friendly features. For this simulation, the AC/DC feature of Electrostatics for 3D component us used to simulate three plane ECVT system. The electric field distribution is plotted using the streamline dataset and the electrical potential value at the center of the pipe is extracted using 3D cut point feature.

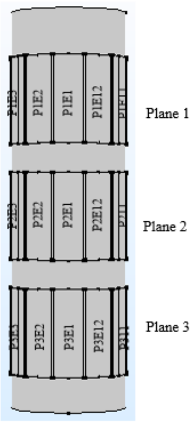
4.1 Electrode and simulation parameter

Simulation test was performed to study the relationship and tendency of the electric field inside the pipe with three planes of electrodes. The distribution of electric fields being captured is analyzed for excitation same plane and different plane. It also involves excitation of the adjacent and farthest electrode. Table 1 shows the pipe and the simulation parameters.

Table 1. Simulation parameters

Parameter	Value
Input Voltage (Vp-p)	10
Pipe content	Water
Material of electrode	Copper-based PCB
Number of electrodes (each plane)	12
Width of electrode	25 mm
Length of electrode	75 mm
Distance between plane	30 mm
Number of planes	3
Outer diameter (O.D.)	110 mm
Inner diameter (I.D.)	100 mm
Length of pipe	450 mm
Pipe Material	Acrylic

An acrylic pipe with an inner diameter of 100 mm is used to place three plane electrodes. Each plane consists of 12 copper-based electrodes with a sensing area of 25mm x75mm. The pipe is filled with water which has a permittivity value of 80. Figure 2 shows that design of the electrodes as well as the indication of the electrode based on the plane number.



Electrode/ plane	Plane 1	Plane 2	Plane 3
E1	P1E1	P2E1	P3E1
E2	P1E2	P2E2	P3E2
E3	P1E3	P2E3	P3E3
E4	P1E4	P2E4	P3E4
E5	P1E5	P2E5	P3E5
E6	P1E6	P2E6	P3E6
E7	P1E7	P2E7	P3E7
E8	P1E8	P2E8	P3E8
E9	P1E9	P2E9	P3E9
E10	P1E10	P2E10	P3E10
E11	P1E11	P2E11	P3E11
E12	P1E12	P2E12	P3E12

Figure. 2. The electrode design and indication for simulation test

For this experimental experiment, there are several methods of dual excitation given. Apart from that, single excitation is also simulated to obtain as a basic comparison factor for other dual methods. Among the dual excitation studied are (1) dual excitation in the same plane with adjacent pairing segmented excitation (2) dual excitation in the same plane with opposite pairing segmented excitation (3) dual excitation in the different plane with adjacent pairing segmented excitation and (4) dual excitation in the different plane with opposite pairing segmented excitation. Table 2 shows the combination of excitation method for single and dual excitation method.

Table 2. Excitation method electrode combination

Excitation method	Electrode position	Electrode excited indication		
Single excitation	N/A	P1E1	P2E1	P3E1
Dual excitation in the same plane	Adjacent	P1E1 - P1E2	P2E1 - P2E2	P3E1 - P3E2
	Opposite	P1E1 - P1E7	P2E1 - P2E7	P3E1 - P3E7
Dual excitation in different plane	Adjacent	P1E1 - P2E1	P2E1- P3E1	
	Opposite	P1E1 - P2E7	P2E1- P3E7	P1E1 - P3E7

For single excitation method, P1E1, P2E1 and P3E1 is used as the excited electrode. For dual excitation in the same plane, there are two electrode positions that are manipulated i.e. adjacent pairing (for example P1E1 and P1E2) is excited and also with opposite electrodes (for example P1E1 and P1E7) are excited. The same method is also used for plane 2 and plane 3. Apart from that, the dual excitation method for different planes is also studied with several electrode pairs for example, for adjacent electrode pairs but on different planes, pairing P1E1 and P2E1 are excited simultaneously. As for the opposite electrode pairs, P1E1 and P2E7 are excited.

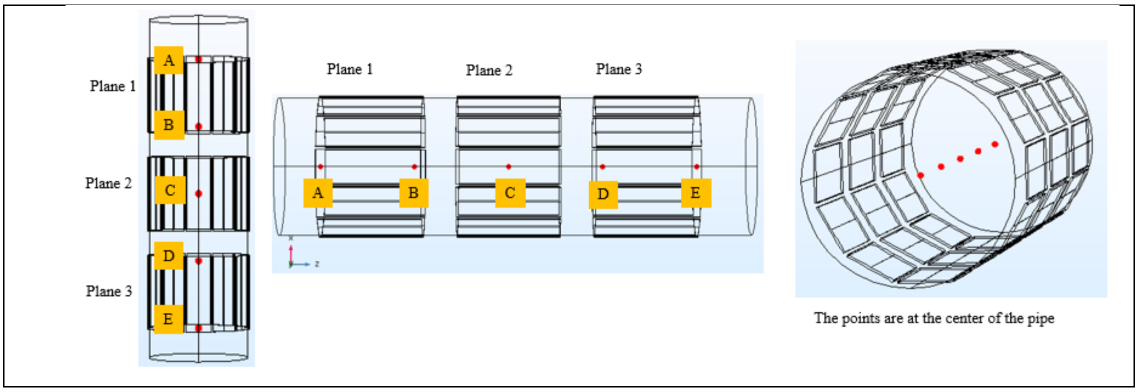
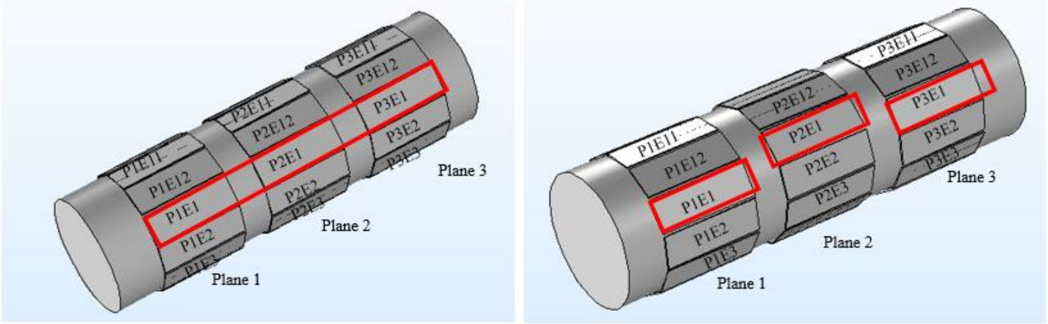


Figure. 3. The five points of data extraction

For this simulation test, the extracted voltage distribution data is in the middle of the pipe. The number of data extracted is as much as five data at five different positions along the three plane ECVT system as shown in Figure 3. The points are indicated as Point A to E with the distance between the points is 4.6 cm. Later the electric field distribution and the voltages at the center of the pipe are extracted and plotted into graphs.

4.2 ECVT parallel and shifted electrode configuration.

There are two types of electrode configuration tested for this simulation. The first configuration is that all electrodes are parallel to all planes, for example P1E1, P2E1 and P3E1 are parallel as shown in figure 4(a). The second configuration is by shifting the second plane electrode position to 15^0 shifted from plane 1 and plane 3 (refer figure 4(b)). for example, P2E1 and the rest of the electrodes in plane 2 is shifted by 15^0 from P1E1 and P3E1. The electrical field and the voltage value at the center of the pipe are captured and recoded as the output of the experiment.



(a) (b)

Figure. 4. The parallel and shifted electrode position

4.3 Electrical field distribution

For the simulation, the fringe effect due to the finite axial length of the electrodes is not considered, which means that the electrical field is believed to be homogeneous in the axial direction. Numerical modeling approaches provide reasonably precise solutions for the respective distributions of physical properties. However, this accuracy is at the cost of unnecessary computing time and energy. In terms of industrial applications, speed, precision, and simplicity are key factors in determining the overall quality of the process used [15].

Figure 5 and figure 6 show the tendency of electric field is captured from COMSOL Multiphysics for both parallel and shifted electrode positions. The red line indicates the electric field line inside the pipe.

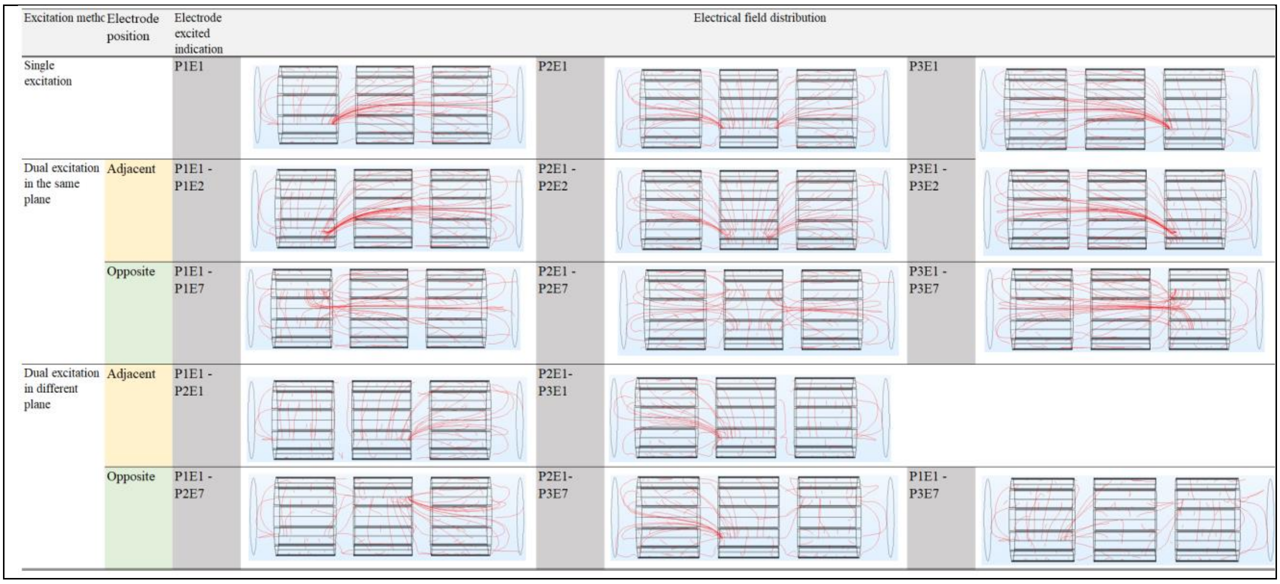


Figure. 5. The electric field distribution of single and dual excitation method for parallel electrode position

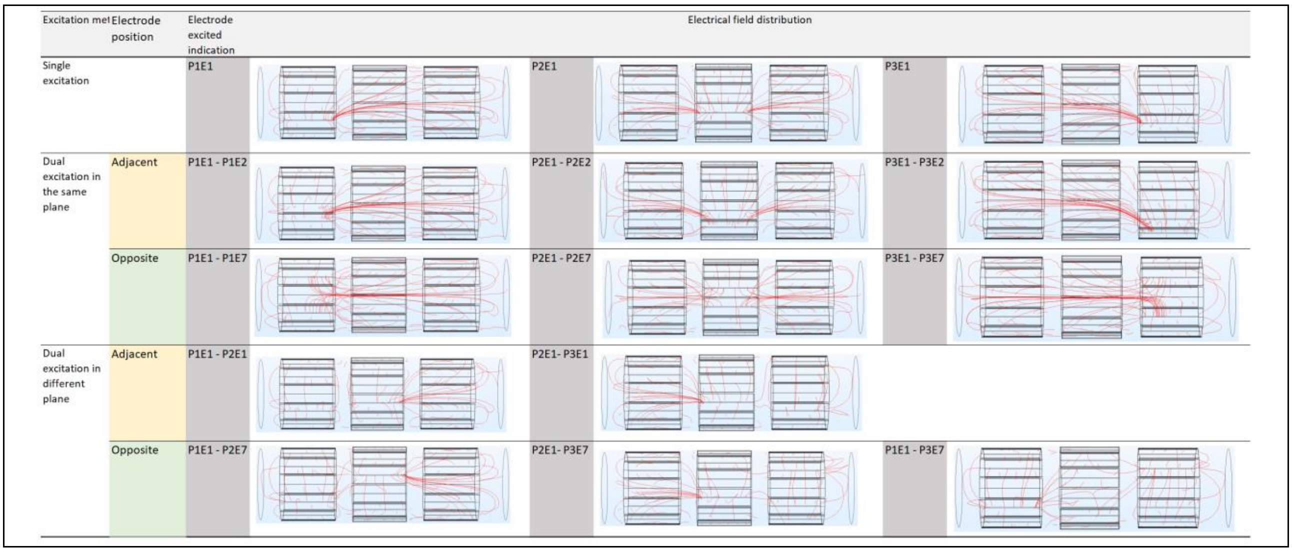


Figure. 6. The electric field distribution of single and dual excitation method for shifted electrode position

For single excitation, the movement of the electric field is clearly visible from the transmitter to the receiver and the same tendency can be observation for parallel and shifted electrode configuration. The same tendency is also clearly seen for dual excitation with adjacent electrode pair. This is because both excited electrodes are adjacent, and the electric field distribution shows the same movement from the transmitter to the receivers. This relates to the capacitance measurement formula.

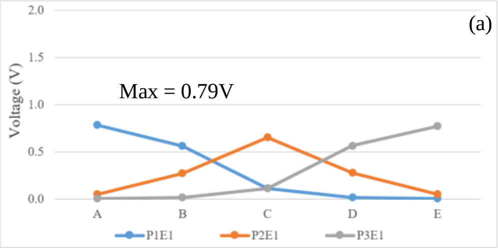
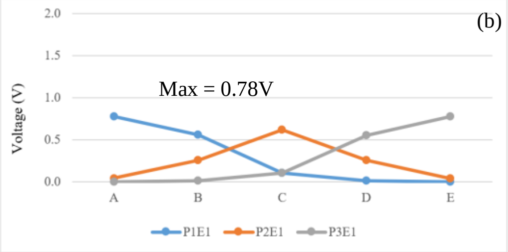
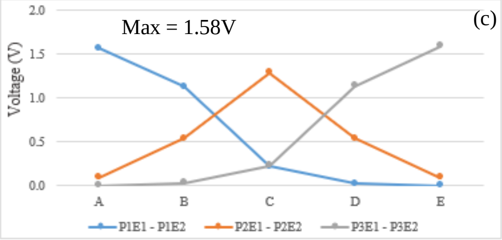
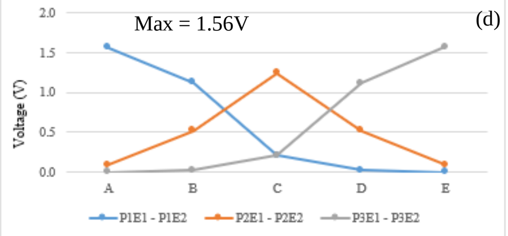
$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{5}$$

where ε_0 is the permiitivity constant of free space, $\varepsilon_r$is the relative permittivity of medium inside the pipe, A is the plate size and d is the distance between of the electrode plates.

For pairing excited electrode on the same plane but in opposite position, for example P1E1-P1E7, P2E1-P2E7 and P3E1-P3E7, the electric field looks more scattered throughout the area in the pipe. The scattered electric field pattern can also be seen on dual excitation in different planes either for adjacent electrode pair (P1E1-P2E1 and P2E1-P3E1) or opposite electrode pair such as P1E1-P2E7, P2E1-P3E7 and P1E1-P3E7. is for P1E1-P3E7, where the electrode positions are farthest from each other. It is reported that multiple excitation methods enhances reconstructed images in the central area and the spatial resolution of the reconstructed images is decreased and improved the ill-posed problem [23] .From the streamline electrical field simulation, users can observe the electric field distribution inside the pipeline for single dual excitations that has been carried out. Next the voltage values at the center of the pipe are recorded, plotted, and discussed in the next section.

4.4 Electrical field distribution

Figure 7 shows the voltage value at the center of the pipe for point A to E for parallel and shifted electrode configuration. The data also plotted the single and dual excitation method. The same pattern tendency of maximum and minimum voltage value at the center for both parallel and shifted electrode configuration. The voltage value of the electric potential value is the highest when the excited electrode is near the point of interest. For example, point A, the voltage value is the highest when P1E1 or equals P1E1 with another electrode. Point E is also high when the electrode on plane 3 is excited by single or dual excitation, and when the electrode on the plane 2 is excited, point C shows the highest voltage value compared to other points. While for the lowest electric potential value is obtained when the point of interest is the farthest away from the electrode being excited either for single or dual excitation. This result indicates that the voltage signal inside the pipe has a magnitude proportional to the excited electrodes.

<table>
<tr><th rowspan="2">Excitation method</th><th colspan="2">Electrode configuration</th></tr>
<tr><th>Parallel</th><th>Shifted</th></tr>
<tr><td>Single excitation</td><td>
</td><td>
</td></tr>
<tr><td>Dual excitation - same plane - adjacent</td><td>
</td><td>
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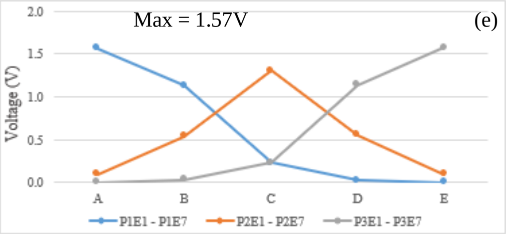
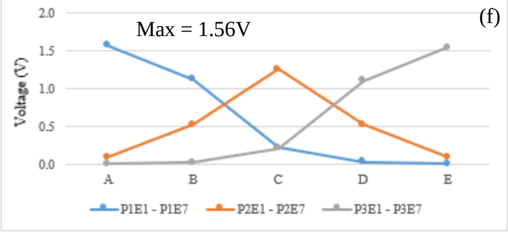
<tr><td>Dual excitation - same plane - opposite</td><td>
</td><td>
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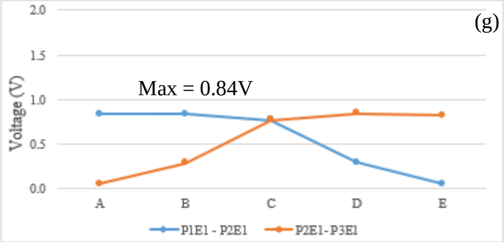
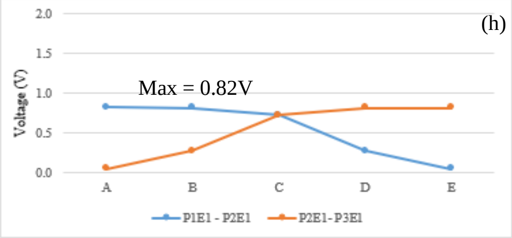
<tr><td>Dual excitation - different plane - adjacent</td><td>
</td><td>
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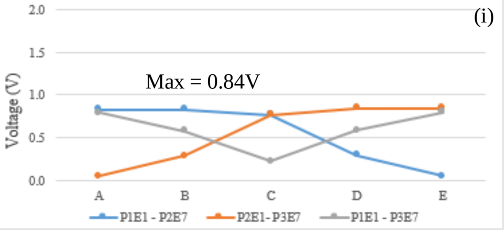
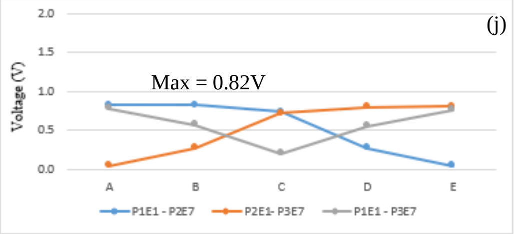
<tr><td>Dual excitation - different plane - opposite</td><td>
</td><td>
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Figure. 7. The voltage distribution at the center of the pipe for parallel and shifted electrode configuration.

Figure 8 shows the comparison of maximum voltage value of same and different plane for dual excitation method for parallel electrode configuration. The dual excitation in the same plane shows higher electrical potential (1.58V) compared to different plane excitation (0.84V), this gives the difference 0.74V. For the excited electrode pair which is in the opposite position gives a difference of 0.73V for the maximum voltage value in the middle of the pipe. This result indicates that same plane excitation configuration slightly more sensitive at the center of the pipe compared to dual excitation with different plane excitation. The maximum electrical potential value for different plane configuration is slightly higher (6%) than single excitation method.

Referring to figure 7 (a) and (c) the voltage value in the middle of the pipe for the adjacent pair electrode is produced slightly higher by 0.01V compared to the opposite pipe electrode. From previous research, it is noted that the adjacent pair electrode can contributes up to 100 times the maximum sensitivity than that of an opposing electrode pair [24] and resulting higher sensitivity at wall area compared to in the middle of the pipe [25]. This result shows that the adjacent pair excitation in the same plane able to produce higher electrical potential in the middle of the pipe.

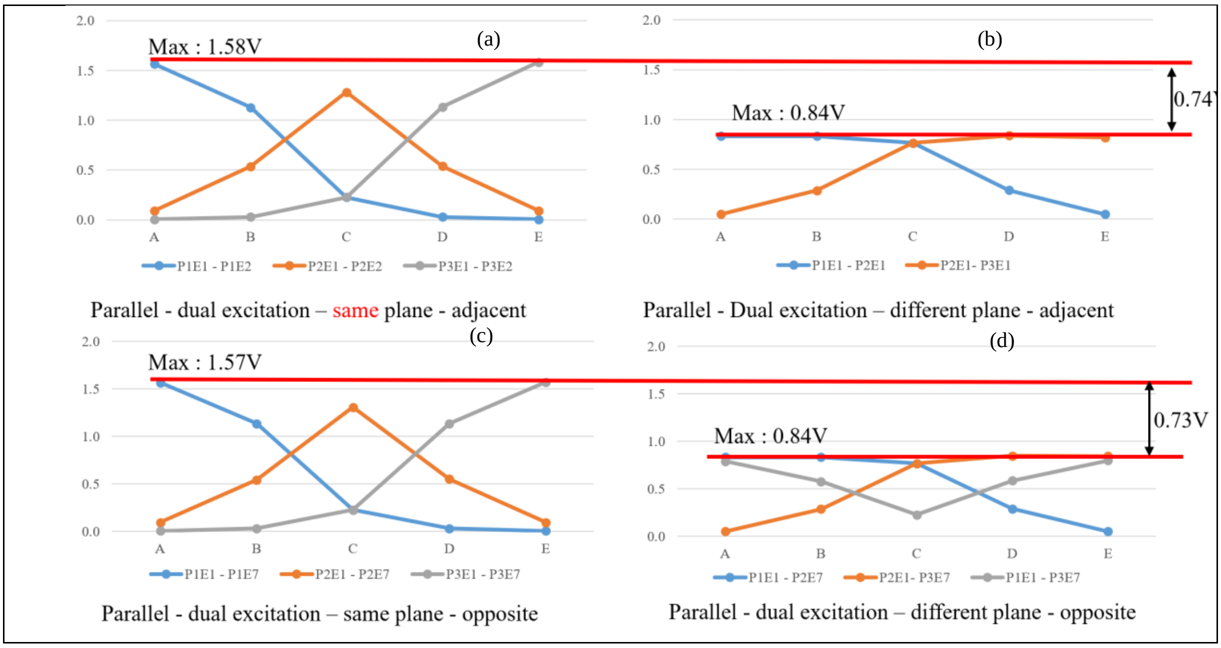

Figure. 8. Parallel plane comparison for same and different plane excitation method

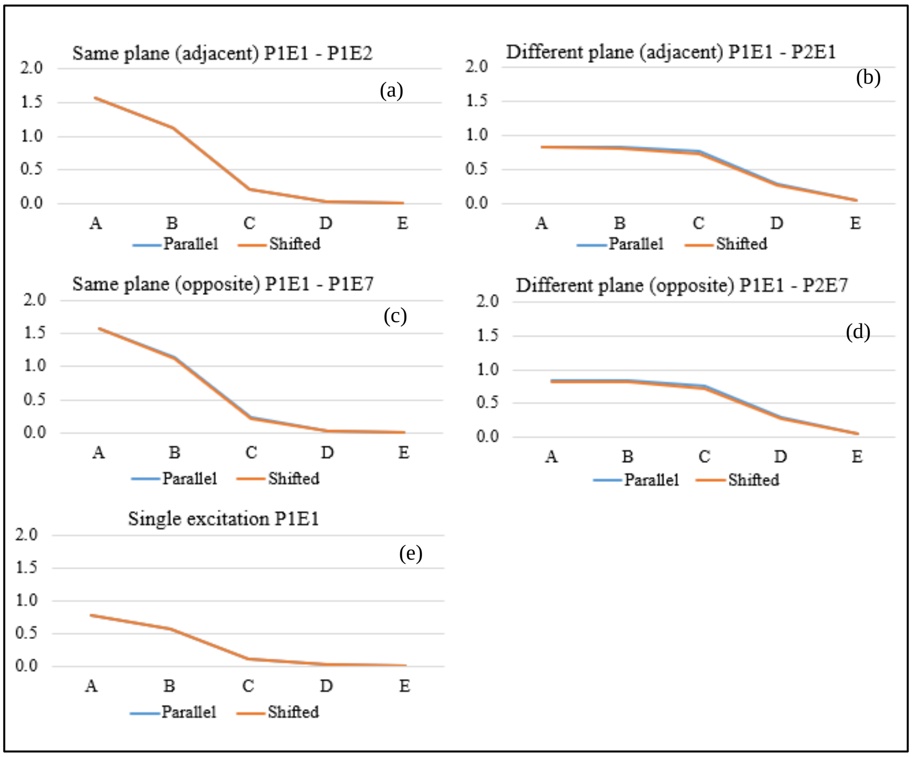

Figure. 9. Comparison of parallel and shifted electrode configuration

Some sample measurements from this simulation are taken from parallel and shifted electrode configuration for comparison purposes as shown in figure 9. Electrical potential in the middle of the pipe does not show a significant difference between parallel and shifted distribution. The data recorded the difference between parallel and shifted electrode configurations with total average difference of 5.05%. From these results, parallel electrodes can be selected to be fabricated into actual experimental setup for appropriate study and application.

5. Conclusion

This paper focuses on simulation of single ang segmented excitation using dual excitation of same and different plane. The study also examines two types of electrode configuration (1) parallel placement of all electrodes in all planes and (2) the electrode on the second plane is shifted by 15° from plane 1 and 3.

The electrical field distributions are captured for all excitation methods. The voltage values at the centre of the pipe are captured at five respective points along the pipe. From the simulation result, it can be concluded that:

1) The voltage value of the electric potential value is the highest when the excited electrode is near the point of interest, which indicates that the voltage signal inside the pipe has a magnitude proportional to the excited electrodes.
2) The dual excitation in the same plane shows higher electrical potential compared to different plane excitation method.
3) the voltage value in the middle of the pipe for the adjacent pair electrode is only slightly higher compared to the opposite pipe electrode.
4) The electrical potential in the middle of the pipe does not show a significant difference between parallel and shifted distribution.

Thus, the result shows that the adjacent dual excitation method in the same plan able to produce high electrical potential at the centre of the pipe. This condition gives more sensitivity in the middle of the pipe and at the pipe wall which can improve the quality of image reconstruction to be applied in experimental setup.

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References

[1] Huang, S. M., Plaskowski, A. B., Xie, C. G., & Beck, M. S. (1988). Capacitance-based tomographic flow imaging system. *Electronics letters*, *24*(7), 418–419.

[2] Marashdeh, Q., Wang, F., Fan, L. S., & Warsito, W. (2007, October). Velocity measurement of multi-phase flows based on electrical capacitance volume tomography. In *SENSORS, 2007 IEEE*, 1017–1019. IEEE.

[3] Ismail, I., Gamio, J. C., Bukhari, S. A., & Yang, W. Q. (2005). Tomography for multi-phase flow measurement in the oil industry. *Flow measurement and instrumentation*, *16*(2–3), 145–155.

[4] Rahim, R. A., Tat, T. C., San, C. K., Fea, P. J., & Chean, L. L.(2004). Capacitance Tomography Techniques for Imaging a Mixture of Water and Oil, *Journal Ind. Technol.*, *13*(2), 8.

[5] Sun, J., Ren, Z., & Yang, W. (2015). 3D imaging with single-plane electrical capacitance tomography sensor. *Electronics Letters*, *51*(3), 222–224.

[6] Marashdeh, Q. M., Teixeira, F. L., & Fan, L. S. (2013). Adaptive electrical capacitance volume tomography. *IEEE Sensors Journal*, *14*(4), 1253–1259.

[7] Marashdeh, Q. (2009). *Validation of Electrical Capacitance Volume Tomography with Applications to Multi-Phase Flow Systems* (Doctoral dissertation, The Ohio State University).

[8] Wang, F., Marashdeh, Q., Fan, L. S., & Warsito, W. (2010). Electrical capacitance volume tomography: Design and applications. *Sensors*, *10*(3), 1890–1917.

[9] Wang, F., Marashdeh, Q., Warsito, W. F., & Fan, L. S. (2008, November). Imaging Gas/Solid Jet Penetration in a Gas-Solid Fluidized Bed Using Electrical Capacitance Volume Tomography. In *Proceedings of AIChE Annual Meeting*.

[10] Gut, Z. (2020). Using electrical capacitance tomography system for determination of liquids in rocket and satellite tanks. *Transactions on Aerospace Research*.

[11] Mukhlisin, M., Baidillah, M. R., & Taha, M. R. (2014). Electrical capacitance volume tomography for measurement soil water infiltration in vessel experiments. *Journal of Central South University*, *21*(1), 358–364.

[12] Wang, A., Marashdeh, Q. M., Teixeira, F. L., & Fan, L. S. (2015). Electrical capacitance volume tomography: A comparison between 12-and 24-channels sensor systems. *Progress In Electromagnetics Research*, *41*, 73–84.

[13] Ahmad, I., Mukhlisin, M., & Basri, H. (2016). Comparisons of Sensor Position for Electrical Capacitance Volume Tomography (Ecvt). *Modern Applied Science*, *10*(4).

[14] Styra, D., & Babout, L. (2010). Improvement of AC-based electrical capacitance tomography hardware. *Elektronika ir Elektrotechnika*, *103*(7), 47–50.

[15] Marashdeh, Q., Warsito, W., Fan, L. S., & Teixeira, F. L. (2006). Nonlinear forward problem solution for electrical capacitance tomography using feed-forward neural network. *IEEE Sensors Journal*, *6*(2), 441–449.

[16] Yang, Y., Peng, L., & Jia, J. (2017). A novel multi-electrode sensing strategy for electrical capacitance tomography with ultra-low dynamic range. *Flow Measurement and instrumentation*, *53*, 67–79.

[17] Senen, M. S., Mohamad, E. J., Ameran, H. L. M., Rahim, R. A., Faizan, O. M., & Muji, S. Z. M. (2017). Simulation Analysis of Dual Excitations Method for Improving the Sensitivity Distribution of an Electrical Capacitance Tomography System. *International Journal of Integrated Engineering*, *9*(1).

[18] Xu, Z., Jiang, Y., Wang, B., Huang, Z., Ji, H., & Li, H. (2017). Sensitivity distribution of CCERT sensor under different excitation patterns. *IEEE Access*, *5*, 14830–14836.

[19] Yang, Y., Peng, L., & Jia, J. (2017). A novel multi-electrode sensing strategy for electrical capacitance tomography with ultra-low dynamic range. *Flow Measurement and instrumentation*, *53*, 67–79.

[20] Saied, I., & Meribout, M. (2016). Electronic hardware design of electrical capacitance tomography systems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*(2070), 20150331.

[21] Mao, M., Ye, J., Wang, H., Zhang, J., & Yang, W. (2015, September). Excitation strategy for three-dimensional electrical capacitance tomography sensor. In *2015 IEEE International Conference on Imaging Systems and Techniques (IST)*, 1–6. IEEE.

[22] Zeeshan, Z., Zuccarelli, C. E., Acero, D. O., Marashdeh, Q. M., & Teixeira, F. L. (2018). Enhancing resolution of electrical capacitive sensors for multiphase flows by fine-stepped electronic scanning of synthetic electrodes. *IEEE Transactions on Instrumentation and Measurement*, *68*(2), 462–473.

[23] Mao, M., Ye, J., Wang, H., Zhang, J., & Yang, W. (2016). Evaluation of excitation strategy with multi-plane electrical capacitance tomography sensor. *Measurement Science and Technology*, *27*(11), 114008.

[24] Yang, W. (2010). Design of electrical capacitance tomography sensors. *Measurement science and technology*, *21*(4), 042001.

[25] Mohamad, E. J., Rahim, R. A., Rahiman, M. H. F., Ameran, H. L. M., Muji, S. Z. M., & Marwah, O. M. F. (2016). Measurement and analysis of water/oil multiphase flow using Electrical Capacitance Tomography sensor. *Flow Measurement and Instrumentation*, *47*, 62–70.

[26] Chala, G. T., Sulaiman, S. A., & Japper-Jaafar, A. (2018). Flow start-up and transportation of waxy crude oil in pipelines-A review. *Journal of non-newtonian fluid mechanics*, *251*, 69–87.