TSSA Journal of Tomography System & Sensors Application Vol. 8, Issue 2, 2025
www.tssa.com.my e-ISSN: 636-9133

Velocity Measurement of Gas-Solid by Means of Single Electrical Capacitance Tomography Sensor

Ahmad Azahari Hamzah[1*], Ruzairi Abdul Rahim[2], Mohamad Zulkeflee Sabri[1], Zaihar Yaacob[1], Muazzin Mupit[1], Mohd Syazwan Mohd Ghazali[1], Edyazuan Azni[1], Mohd Nizam Zahari[1], Yasmin Abdul Wahab[3]

[1]Section of Chemical Engineering Technology, Universiti Kuala Lumpur. Malaysian Insititute of Chemical and Bioengineering Technology (UniKL MICET), 78000, Alor Gajah, Melaka
[2]Faculty of Electrical, Universiti Teknologi Malaysia 81310 Johor Bahru, Johor, Malaysia
[3]Faculty of Electrical & Electronics Engineering Technology, Universiti Malaysia Pahang Al- Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

Corresponding author* email: ahmadazahari@unikl.edu.my

ABSTRACT

Velocity is one of the crucial parameters in the multiphase flow especially gas-liquid two-phase flow. Electrical capacitance tomography (ECT) offers robust, inexpensive, non-invasive and non-intrusive techniques in quantifying multiphase flow phenomena. This paper demonstrates methods to estimate average axial velocity by using a novel approach by means of single plane ECT sensor. The proposed method has been compared with a high-speed camera. Based on the three specific cases, all methods successfully estimate the axial average velocity with maximum percentage error is 3.431%.

Keywords: Electrical Capacitance Tomography, Single plane, Velocity Measurement

1. Introduction

There are huge numbers of industrial operations that involved with contacting gas and solid phases such as petrochemical, power generation, biocatalysts, separations, and food processing. Up till now, they are no universal technique to dismantling the complexity of this flow behavior. One of the crucial parameter to interpret this type of flow is velocity in order to design an effective and efficient cost in particular industrial processing. Among possible technique for estimating velocity are particle image velocimetry, tracer, simulation, and tomography. One kind of interesting measurement technique with non-invasive and non-intrusive in collecting information data is tomography technique specifically electrical based. This measurement offers a unique technique to solve the complexities of the internal structure of an object without invading it [1]. The most mature electrical tomography among other modalities in industrial application is electrical capacitance tomography (ECT) [2].

Basically, ECT technique reconstructed the electrical permittivity of the close domain containing dielectric properties of materials from the electrical capacitance data collected at all pairs of the electrode. A single electrode is excited by AC voltage at one time which so-called transmitter electrode while the rest which are receiver electrodes are kept at ground potential and at the same time, the displacement currents are computed. For N electrode number, its contain m = N(N - 1) independent measurements. This measurement type is called the low-Z scheme [3]. The measurement principles of an ECT system for 8 electrodes can be seen in Figure 1.

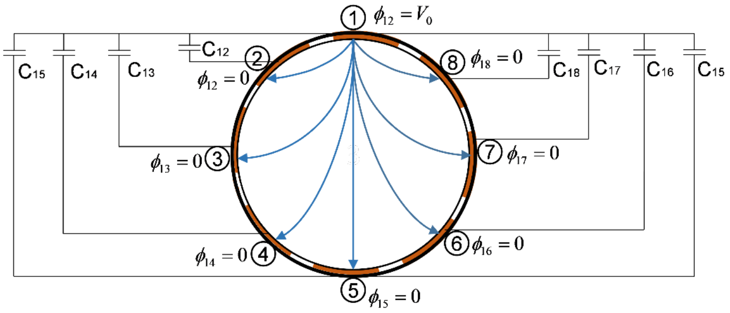


Figure 1. Measurement principle of an ECT with 8 electrodes.

In calculating capacitance between the electrodes, Poisson equation was applied which is given by:

$$\nabla \cdot [\varepsilon(\mathbf{r})\nabla \phi_{ij}(\mathbf{r})] = 0 \tag{1}$$

where $\varepsilon(\mathbf{r})$ is the relative permittivity, $\phi_{ij}(\mathbf{r})$ is potential at a position $(\mathbf{r})$ and ∇ is the divergent operator. The charge on the receiving electrode *j* when electrode *i* being the source, Q_{ij} can be calculated by using Gauss's law:

$$Q_{ij} = -\oint_{\mathbf{r} \subseteq \Gamma_{ij}} \varepsilon(\mathbf{r})\nabla \phi_{ij}(\mathbf{r}).\mathrm{d}\mathbf{r} \tag{2}$$

where Γ_{ij} is an area of the total capacitance for electrode *ij*. Then, the capacitance between excite and measure electrode, c_{ij} can be calculated as follow:

$$c_{ij} = -\frac{1}{V_{ij}} \oint_{\mathbf{r} \subseteq \Gamma_{ij}} \varepsilon(\mathbf{r})\nabla \phi_{ij}(\mathbf{r}).\mathrm{d}\mathbf{r} \tag{3}$$

where V_{ij} is the potential difference between the *i* and *j* electrodes. This equation also is known as forward problem where the capacitance is calculated based on permittivity distribution and conversely inverse problem where permittivity distribution is calculated from capacitance data [1, 4, 5, 6]. ECT successfully applied on the fluidized bed in defining solid concentration and finding optimal conditions [7].

Usually, velocity technique by tomography mainly focused on dual plane cross-correlation method to determine the time delay in the time domain next to calculate average velocity. In this work, a new non-invasive method was introduced to calculate the average vertical velocity by means of single plane ECT.

2. Velocity Measurement by ECT

2.1 Current Approaches

Commonly, cross correlation frequently studied especially in signal processing to find the similarity of two sequences as a function of time. Tomography applied this technique on the dual plane of electrodes which sets placed at an appropriate distance, then the data can be correlated to measure the average velocity. Classical cross-correlation function, R_{12}, between capacitance measurement $C_1(t)$ and $C_2(t)$ at downstream and upstream plane at a particular time (t) respectively is defined as follow [8]:

$$R_{12}(\tau) = \lim \frac{1}{T}\int_0^T C_1(t)C_2(t+\tau)dt \tag{4}$$

where τ is the time delay between two capacitance measurement and T is the sampling time. In another word, $R_{12}(\tau)$ can be specified as for how much similarity of both capacitance measurements while $C_2(t)$ is shifted in time by τ. The cross-correlation function reaches the maximum value when $\tau = \tau_{\max}$ and this delay is estimation transit time of solid between two planes. Average axial velocity, V can be calculated by using the distance between two sensors, L and estimation transit time as follow:

$$V = \frac{L}{\tau_{\max}} \tag{5}$$

Equation (1) can be written in discrete form as below:

$$R_{12}(\tau) = \sum_{t=0}^{T-1} C_1(t)C_2(t+\tau) \tag{6}$$

This method is called signal to signal (STS), which raw capacitance between upstream and downstream capacitance measurement is cross-correlated.

2.2 A New Approach

This paper introduced a new method by means of a single plane to calculate the average axial velocity. The advantages of this method than current approaches were only a single plane is needed, fast calculation, without any costly software for analyzing and no image reconstruction involved. The concept is based on calculating the total time of raw capacitance value from ECT system which above the boundary set and dividing with the electrode length to gain the average axial velocity. To achieve this purpose, ECT sensor should design as closest to earth screen for both ends to eliminate any 3D effect. Average axial velocity can be calculated as follows:

$$V = \frac{L_{ele}}{\Delta t_s} \tag{7}$$

where, L_{ele} is electrode length and Δt_s is total time of raw capacitance value which above the boundary set and can be calculated as below:

$$\Delta t_s = t_2 - t_1 \tag{8}$$

where t_1 and t_2 are the starting time when the capacitance measurement is higher than boundary set and ending time when the one of capacitance data before lower than boundary set respectively. The boundary set is capacitance measurement when low permittivity material is fully occupied in ECT sensor. The rough idea is shown in figure 2. The drawbacks for this system is fast ECT system is needed to capture every each capacitance changes through the sensor.

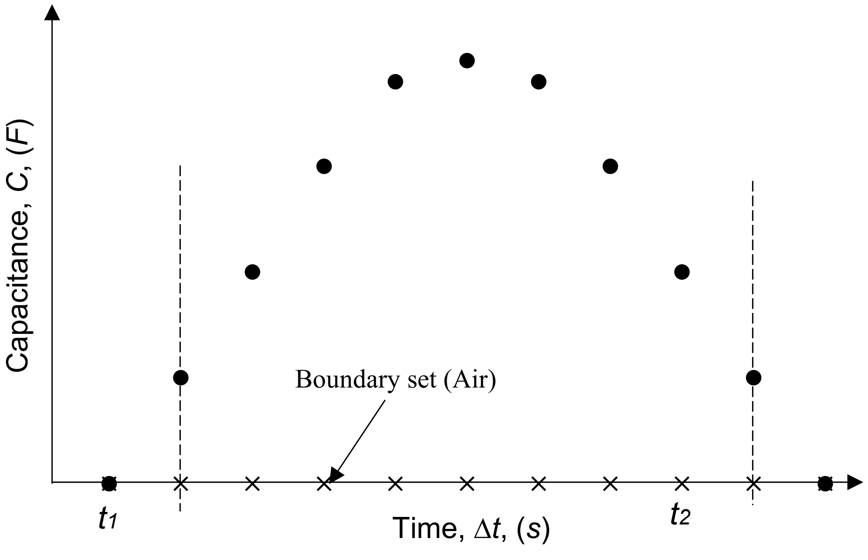


Figure 2. Total time determination

3. Experimental Set-up and Condition

3.1 ECT Sensor Design

The sensor was designed with inner wall diameter, $ID = 46$ mm and it's thickness, $\Delta x = 2$ mm by the acrylic pipe. The sensor is made for two planes with each plane consists of 8 square measurement electrodes while dimension is 16 mm x 100 mm and connected to ECT system via coaxial cable at the top and discharge resistor 1MΩ at the bottom. The angle between two neighboring electrodes is 45°. To reduce external noise, three earthed screens was applied which are an outer screen (185 mm x 140 mm) to prevent interference especially external noise, two axial screens (157 mm x 20 mm) at both ends of measurement electrodes to reduce external noise and 3D effect and radial screens (2 mm x 104 mm) to reduce the standing capacitance between two adjacent electrode pairs [2]. Figure 3 shows the structure of an ECT sensor design.

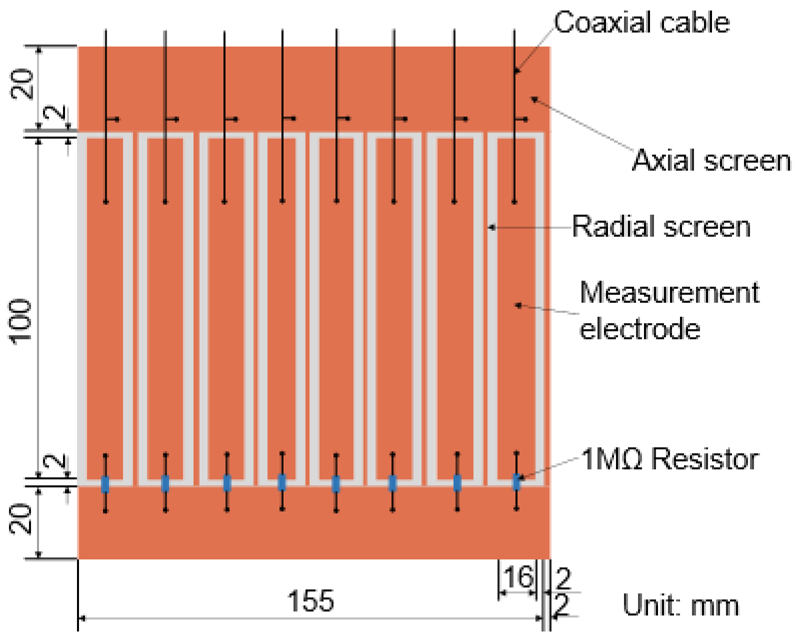


Figure 3. Measurement sensors structure

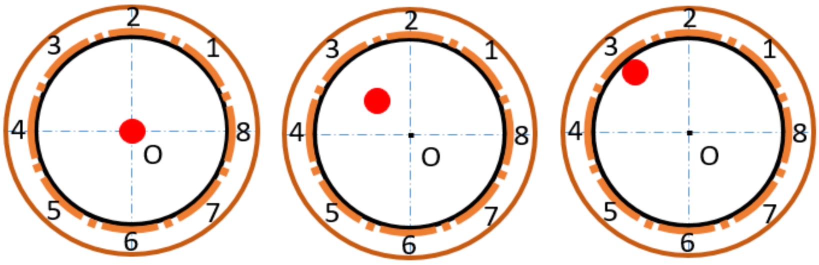
3.2 Experimental Conditions and Method

The calibration for C_{ij}^{L} of low capacitance value was carried out under the condition of only air at room temperature, T_r = 298K (25°C) for all the electrodes pairs. The calibration for C_{ij}^{H} of high capacitance value with PMMA pellets at the T_r and volume, $V_p = 5.94 \times 10^{-4}$ m^3 inside the pipe which fitted with ECT sensor for all the electrodes pairs was performed. After completing the calibration process, the PMMA pellets were discharged from the bottom of the pipe. PMMA ball was set at three different locations which are case 1 in the middle of column (0,0,0,0°), case 2 with the same length between sensor and center position, (-7,7,0,135°) and case 3 which is near to pipe wall, (-14,14,0,135°).

By using the low-Z scheme, the ECT system setting up to inject 16 Vp-p and 160 kHz signal for all electrode transmitter to measure the capacitance value for all the electrodes pairs. The normalization capacitance $\overline{C}_{ij,t}$ is calculated based on the measured capacitance value as below:

$$\overline{C}_{ij,t} = \frac{C_{ij,t} - C_{ij}^{L}}{C_{ij}^{H} - C_{ij}^{L}} \tag{9}$$

$\overline{C}_{ij,t}$ is equal to 0.00 and 1.00 when fully occupied with air and PMMA pellet in pipe respectively. Specifically, for case 1, $\overline{C}_{26,t}$ is considered while $\overline{C}_{24,t}$ for case 2 and $\overline{C}_{23,t}$ for case 3 to determine time lag in line average vertical velocity for both dual and single plane of ECT sensor. All the experiments are repeated at least three times and the average value is presented in this reports.



Case 1 Case 2 Case 3

Figure 4. Position of PMMA ball

4. Results

Figure 5 shows the relationship between normalized capacitance measurement with elapsed time of average vertical velocity by means of ECT single plane sensor for case 1,2 and 3 with $V_p = 0.171$, 0.236 and 0.382 m/s respectively. One pair of normalized capacitance measurement is selected for each case to further analysis which is $\overline{C}_{26}$ for case 1, $\overline{C}_{24}$ for case 2 and $\overline{C}_{23}$ for case 3. This pair was chosen as more sensitive compared to the rest. The dashed line in the graphs represents the boundary set which is only air occupied in the vertical pipe as describe in figure 5. The behaviour of normalized capacitance measurement is a similar pattern to dual plane ECT results which gradually increasing at the beginning until reached the maximum peak at the mid of sensor length then gradually decreased until reach the end of the sensor. The calculation just started after the normalized capacitance measurement is higher than boundary set as t_1 while stop counting the elapsed time when the one last before the measurement is lower than boundary value as t_2. The maximum time lag can easily be counted by using Equation 9 as aforementioned before. Table 1 shows the time delay estimation for velocity measurement by single plane ECT sensor.

Table 1. Time delay estimation by single plane ECT sensor.

	Time delay, Δt_s (s)		
V_p (m/s)	Case 1	Case 2	Case 3
0.171	0.636	0.585	0.580
0.236	0.440	0.420	0.426
0.382	0.248	0.263	0.268

4.1 Average Vertical Velocity

Velocity estimation by single plane ECT sensor was quantitatively compared with velocity captured by a high-speed camera for case 1,2 and 3 for validation purpose. Three velocities calculated by a high-speed camera are 0.171, 0.236 and 0.382 m/s. Figure 5 shows a plot of average vertical velocity by means of single ECT plane. The line at both left and right edge on each plot functionally to show how the velocity calculation by ECT to a high-speed camera diverge.

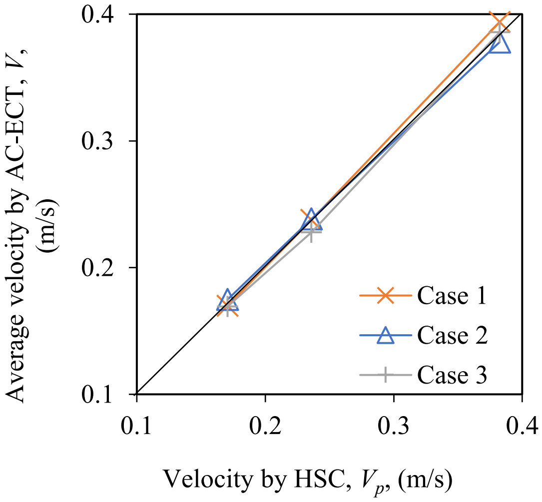


Figure 5. Average axial velocity by single plane ECT sensor

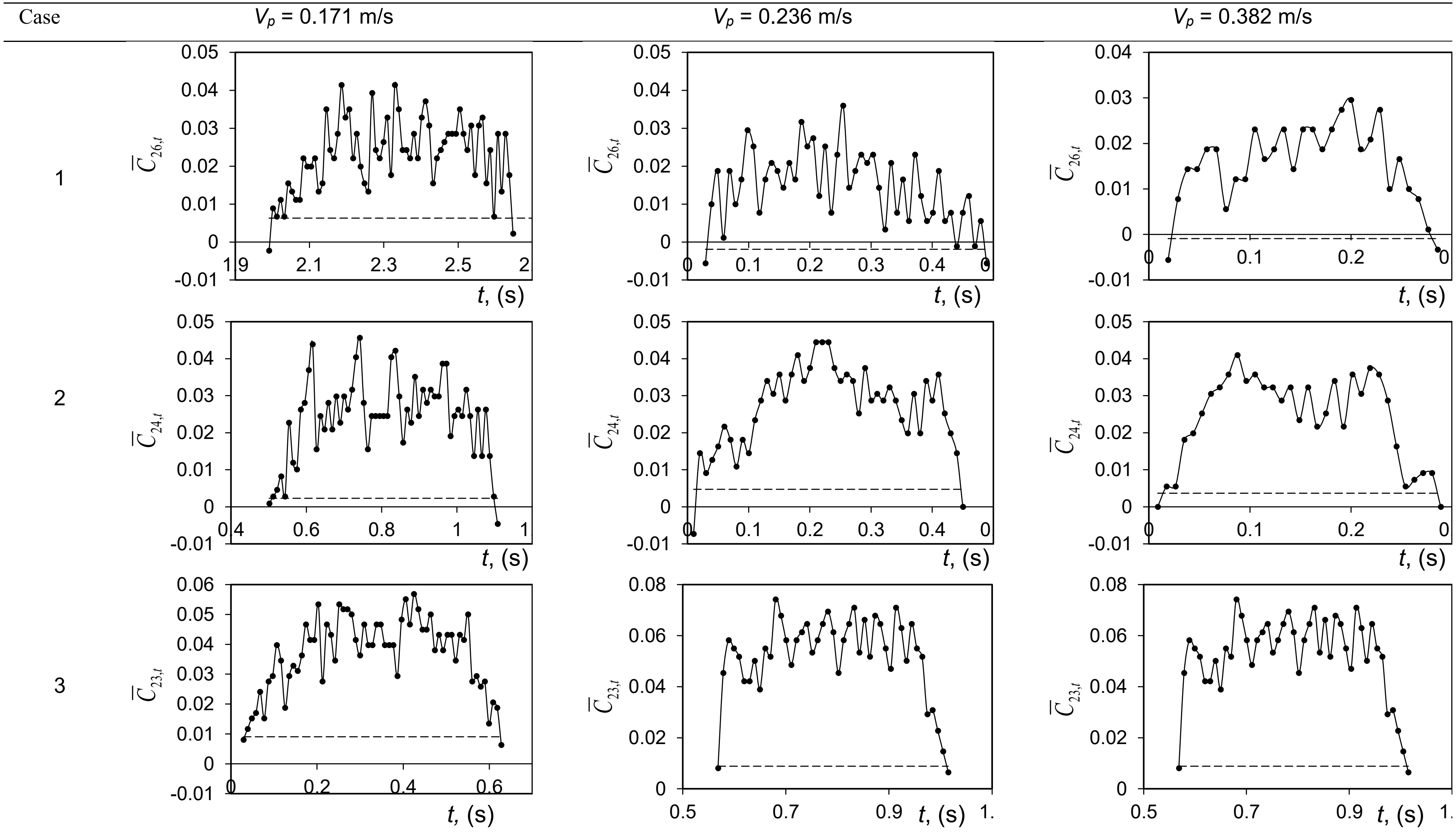


Figure 6. Time lag calculation by means single plane ECT electrode. (—) is normalized capacitance value when PMMA ball is crossing ECT sensor and (---) is a boundary set as stated in Figure 2.

5. Conclusion

Non-invasive velocity measurement for the gas-solid two-phase flow was done by using single plane ECT sensor. Single plane ECT system measurement has its own capability in determining velocity without using any expensive commercial mathematical software. This method used a simple assumption which time delay is equal to total elapsed time above boundary set. These studies show both single plane ECT sensors accomplished to measure the average axial velocity. This pilot study can be used in industrial application not limited to gas-solid two-phase flow exclusively.

References

[1] A. A. Hamzah, A. R. Ruzairi, M.S. Takriff, E.J. Mohamad, J. Pusppanathan, I. N. Azman, M.S. Mohd Ghazali, M.Z. Sabri2, K.F. Mohrab, F. Ghafar, M.N. Zahari. Application of Electrical Resistance Tomography in an Oscillatory Baffled Column for Gas-Liquid Two-Phase Flow. International Journal of Integrated Engineering, Vol. 11 No. 6 (2019).

[2] W. Yang, "Design of electrical capacitance tomography sensors," *Meas. Sci. Technol.*, vol. 21, no. 4, p. 042001, Apr. 2010.

[3] A. Neumayer, M., Zangl, H., Watzenig, D., Fuchs, *New Developments and Applications in Sensing Technology*. 2011.

[4] A. A. Hamzah , R. A. Rahiom, E.J. Mohamad, J. Pusppanathan, K. A. Kadir, H.L.M. Ameran, M. N. A. Mohamed. Simulation Studies on Image Reconstruction Algorithm for Portable Electrical Capacitance Tomography. International Journal of Integrated Engineering, Vol. 10 No. 8 (2018)

[5] Ø. Isaksen, "A review of reconstruction techniques for capacitance tomography," *Meas. Sci. Technol.*, vol. 325, pp. 325–337, 1996.

[6] Hanis Liyana Mohmad Ameran, Ahmad Azahari Hamzah, Ruzairi Abdul Rahim, Fatin Aliah Phang, Nor Hasrul Akhmal Bin Ngadiman, Yasmin Abdul Wahab, Jaysuman Pusppanathan. Sensitivity Mapping for Electrical Tomography Using Finite Element Method. International Journal of Integrated Engineering, Vol. 10 No. 4 (2018) p. 64-67.

[7] C. Wang, Z. Lv, and D. Li, "Experimental study on gas – solids flows in a circulating fluidised bed using electrical capacitance tomography," *Powder Technol.*, vol. 185, pp. 144–151, 2008.

[8] Ahmad Azahari Hamzah, Ruzairi Abdul Rahim, Mohamad Zulkeflee Sabri, Mohd Razealy Anuar, Nor Shahirah Mohd Nasir, Elmy Johana Mohamad, Jaysuman Pusppanathan. Velocity Measurement by Electrical Capacitance Tomography: A Simulative Study. AIP Conf. Proc. 2923, 020016 (2024)