



Electrical Capacitance Volume Tomography (ECVT) for industrial and medical applications-An Overview

¹Mohammed S.Aljohani

¹ Department of Nuclear Engineering, King Abdul Aziz University, KAU, P. O. Box 80204, Jeddah 21589 Saudi Arabia

Abstract

Tomography is a non-invasive, non-intrusive imaging technique allowing the visualization of phase dynamics in industrial and biological processes. This article reviews progress in Electrical Capacitance Volume Tomography (ECVT). ECVT is a direct 3D visualizing technique, unlike three-dimensional imaging, which is based on stacking 2D images to obtain an interpolated 3D image. ECVT has recently matured for real time, non-invasive 3-D monitoring of processes involving materials with strong contrast in dielectric permittivity. In this article, ECVT sensor design, optimization and performance of various sensors seen in literature are summarized. Qualitative Analysis of ECVT image reconstruction techniques has also been presented.

Indexing terms/Keywords

Electrical capacitance volume tomography; 3-d imaging; 3-d capacitance sensor; process tomography

Academic Discipline And Sub-Disciplines

Physics, Medical Physics applications, Industrial Physics applications.

Subject Classification

Electrical Capacitance Volume Tomography

medical and industrial applications of Electrical Capacitance Volume Tomography

Type (Method/Approach)

An overview of Progress in the field of Tomography has been presented in this paper. The advancement and application of electrical capacitance volume tomography in medical field and industrial usage has been presented. The image reconstruction techniques has become the essential part in medical field. However, the image reconstruction sensors performance and design has also been summarized.

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1. Introduction and Background

Tomography has evolved as a non-invasive imaging technique for visualization of internal objects without the superposition of overlying and underlying structures contrary to conventional X-ray radiography [1]. It is used to acquire time-varying spatial material distribution information for inaccessible objects during monitoring of multiphase flow systems, chemical reactors, pneumatic conveying systems, and combustion processes, thereby improving the efficiency, safety, and reliability of systems, as well as reducing energy consumption and pollutant emission. Research and Development in tomography instrumentation dates back as 1930's with the work of Alessandro Vallebona and Bernard Ziedes des plates. In early 1960's the work of G. N. Hounsfield, A. M. Cormack and other researchers has led to the advent of computed tomography, where by cross-sectional imaging technique has provided diagnostic radiology with better insights into pathogenesis of human body [2]. Computed tomography flourished with the development of a better image reconstruction algorithm, called filtered back projection algorithm [3, 4].

Multi-Phase flows employed by industries such as pharmaceuticals, nuclear, food, petrochemicals, etc. Such process has characteristics phase interaction between gas-solid, gas-liquid and gas-liquid-solid phases. A characteristic of multi-phase flow is the presence of one or several interfaces separating the components. Multi-phase flows are characterized by dynamic changes in flow structure depending on phase-fraction and velocities of individual components. Knowing the Phase fraction permits calculation of pressure gradients and losses and also helps in estimation of the flow regime, their transition and instability [5]. Tomography has been evolved and still developing, as a tool for qualitative and quantitative interpretation of process dynamics in industrial domains [6].

For Industrial applications, the selection of a tomography system depends on (a) Phase fraction parameters to be studied (velocity, size, etc.) (b) the required information about the process and its intended purpose (Optimization of equipment, Laboratory investigation, Process measurement of control), (c) and the process operating condition (ambient operating condition, safety implications, ease of maintenance) [6]. Early in 1970s, tomography techniques employing radiation/ionizing sources such as X-rays/Gamma rays were described for industrial tomography. But these techniques yielded poor temporal resolution in addition to their cost and safety constraints [6]. In order to employ safer sensing techniques, Ultrasonic, Magnetic and electrical techniques were suggested [7, 3].

Electrical Capacitance Tomography has seen increased interest due to its non-invasive, non-intrusiveness, low cost, employment of non-hazardous radiations and its suitability for several of vessels. Electric Capacitance Tomography was introduced in US Department of Energy, Morgantown energy technology centre in 1980s, to measure fluidized Bed System [6]. Thereafter, Capacitance tomography techniques have been studied and employed to measure oil concentrations in wells, pneumatic conveyors, pharmaceutical bed dryers phase fraction measurement in multiphase flows etc [8].

Several researcher have used the ECT in different fields of Science. Aining Wang et al., 2014 [45] has measured the pulsating trickled bed by electric capacitance volume tomography (ECVT). They had developed the pulse structure and illustrate the transient conditions. They also observed that the liquid holdups in gas and liquid zones are solely dependent on the gas flow rate. They also used the ECVT for 3D real time imaging of flow structure in bubble columns of straight-cylinder shape and a tapered-cylinder shape with porous and orifice gas distributors (Aining Wang., et al 2014b) [46]. Qussai M. Marashdeh, 2014 [47] has introduced the adaptive ECVT based upon the number of small individual sensors to comprise synthetic capacitance plates of different plates of different sizes and shapes. They suggested that the adaptive concept paved the way for ECVT to be applicable in scenarios requiring higher resolution and dynamic imaging reconstruction. They have applied previous the suggested technique to image the flow of granular matter with different electrical properties in cylindrical vessels. Then they have used the measurement data are then used to reconstruct cross-sectional images of both permittivity and conductivity distributions (Qussai Marashdeh, et al., 2008) [48]. C. Rautenbach et al 2013 [49] has carried out a comparative study of ECT and time resolved x-ray tomography investigated the electrical capacitance tomography (ECT) tomograph and a time-resolved X-ray tomography tomograph. The study was performed on spherical glass particles with various particle size distributions that could mainly be classified as Geldart B or D particles. They found that the particle with widest size has larger discrepancy with theory [49].

Recent studies have shown the application of ECT in medical imaging [9]. Electrical Capacitance technique faces the challenge of limited spatial resolution it can provide, due to limitation in sensors that can be placed around the sensing area. Spatial resolution could be increased by increasing the number of sensors, but this could limit the area of sensing plates and thereby decrease SNR. Measurement resolution is depended on its sensor design, whereby proper grounding and shielding are needed [10]. Warsito P. 2014 [40] has developed a novel ECVT design for the 3D imaging of breast cancer. He also used the same technique for 4D ECVT design for brain tumour diagnosis [42].

In this paper, a review of progress in Electrical Capacitance Volume Tomography (ECVT) has been presented. ECVT is a direct 3D visualizing technique, unlike three-dimensional imaging, which is based on stacking 2D images to obtain an interpolated 3D image. ECVT has recently matured for real time, non-invasive 3-D monitoring of processes involving materials with strong contrast in dielectric permittivity. In this article, ECVT sensor design, optimization and performance of various sensors seen in literature are summarized. Qualitative Analysis of ECVT image reconstruction techniques has also been presented.

2. Electrical capacitance volume tomography

A typical, ECT system consists of transducer electrodes, fitted around the vessel for investigation, a data collection system which is embedded with plate selection protocol and analog to digital conversion for PC interface, thirdly a PC is

employed where an appropriate image reconstruction algorithm is employed to estimate the permittivity distribution around the vessels (Fig 1). In particular, electrical capacitance tomography (ECT) is an imaging modality that has been developing over the past two decades for multi-phase flow imaging. ECT has been used to capture cross sections of averaged flow distributions over the length of the vessel. The use of ECT has been extended to quantify transient flow behaviour through measurement of 3-phase velocities in fluidized beds [11]. The Accuracy of ECT images have improved significantly through the employment of optimization reconstruction techniques [12]. Techniques known as Neural Network multi criterion optimization image reconstruction technique (NN-MOIRT) has enabled 3 phase imaging based on ECT as well as quasi 3D ECT imaging [13].

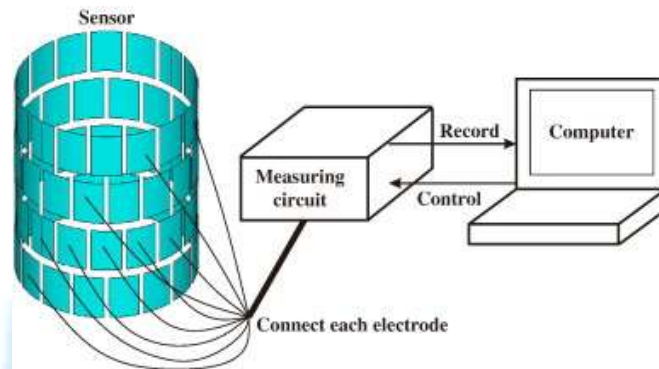


Fig 1. Scheme of typical 3D ECVT system. [47]

However, the velocity measurements of phase fractions are restricted by the 2D capability of the ECT technology and the velocity profile over the length of the vessel is obtained by cross correlation of ECT images over different space or time slots [11]. This limitation and advances in optimization image reconstruction (NN-MOIRT) have led to the development of electrical capacitance volume tomography (ECVT) for direct 3D imaging [13].

Electrical Capacitance Volume tomography (ECVT) is a direct 3D visualizing technique, unlike traditional 3D imaging, based on stacking 2D images to obtain an interpolated 3D image. ECVT is a recently maturing technique for real time, non-invasive 3-D monitoring of processes involving materials with strong contrast in dielectric permittivity. ECVT has the potential to provide qualitative and quantitative information of the dynamic flow behavior of the process under investigation [11]. It has the potential for real time volume tomography, suitable to irregular geometries with cheap sensors [11]. Studies and Research in ECVT have been conducted from the labs of Ohio state University (Qussai, M. et al) in 2005[13]. Researchers from Bath University have developed a temporal based image reconstruction based on inter frame correlation for 4D imaging [14].

Electrical Capacitance volume tomography is based on reconstructing the internal permittivity distributions based on boundary capacitance measurements. It employs the non-linear distribution of electric Field lines to reconstruct a volume image of permittivity distribution inside the imaging area [12]. Unlike, ECT where only 2D variation of electric field in radial direction is considered. The fringing effect of electric field is viewed as an undesired component for 2D image reconstruction. However, the fringing effect of electric field distribution is employed in ECVT to produce field distribution in axial direction for 3D imaging.

A typical ECVT system consists of an ECVT sensor, data acquisition system, and computer for data recording and image reconstruction. ECVT measures capacitances between all electrode pairs of the ECVT sensor with N channels, which gives a total N (N-1)/2 independent capacitance measurements. The measurement here is a set of normalized independent capacitances from the sensor. ECVT sensors are designed to provide an equal distribution of electric fields in all three dimensions. 3D ECVT sensor design is an evolving topic and two components of ECVT sensor are considered in establishing 3D field variations: 1) number of plates and 2) shape of plates. The acquisition hardware and reconstruction techniques are still topics for research [15].

3. Sensor Design

Capacitance tomography belongs to soft field category of tomography techniques, where the interrogating electric field distribution depends on the dielectric distribution in the media. Due to the nonlinear dependence of electric field and dielectric distributions, nonlinear image reconstructions with optimizing certain objective functions have to be implemented.

The electric potential and permittivity distribution are described by Poisson equations as:

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

where $\epsilon(x, y, z)$ is the permittivity distribution, $\nabla \phi(x, y, z)$ is the electric field distribution, $\rho(x, y, z)$ is the charge density. The measured capacitance between the *i*th and *j*th electrode for an 'N' electrode system is given as

$$C = \frac{1}{\nabla v_{ij}} \iint_A \epsilon(x, y, z) \nabla \phi(x, y, z) dA \tag{2}$$



A is the surface area enclosing the j th electrode, ∇V_{ij} is the potential applied between electrodes.

The electric field distribution is non-linearly dependent on the dielectric distribution as evident from the Poisson equation (Eq 1). Eq (2) shows that the capacitance measurements between electrodes are dependent on the electric field, which in turn depends on the permittivity distributions and also on the electrode dimensions and orientation. From Eq (1) and Eq (2), one can optimally design the sensors dimensions, orientations, shape and number of electrodes considering the process under investigation.

When both the number, dimensions, shape, layers, orientation and process under study have great importance with regards to sensor performance, as evident from Eq (1) and Eq (2), their optimal design and selection are seldom discussed. Most of the works have arbitrarily taken a particular sensor configuration based on few criteria such as shape of the vessel, and process under investigation. Fewer works have concentrated in optimally designing the sensors [16]. Different techniques such as finite-element methods [17-19]. Finite volume methods [20], soft computing techniques [21] have been employed in sensor design and optimization. MATLAB, ANSYS and COMSOL are Multi Physics commercially available packages that have been employed to simulate the sensor performances.

No work has been seen in literature to solve the Poisson equation (Eq 1) and Eq 2 through suitable technique in order to determine the optimal shape and dimensions of sensors. Most of the work on non-intrusive capacitance tomography has employed flexible copper plastic laminate, in which electrodes are etched with required electrode pattern using photolithography techniques and then wrapped around the pipeline or vessel where the process is under investigated. Other works have employed rectangular aluminium electrodes pasted around the pipe geometry under investigation [22]. The latter technique has shown poor precision in capacitance measurements.

3.1 ECVT sensor configurations

Sensor design for non-intrusive capacitance tomography has been primarily based on reconstructed images as whether 2D or 3D reconstruction is intended. Thus sensors are classified as two dimensional and three dimensional capacitance sensors. The electric field distribution in 2D ECT is assumed only in radial direction and fringing effect is considered undesirable as it introduces artefacts in image reconstruction [13]. ECVT for volume imaging is based on utilizing the fringing effect to produce field variation in axial direction. Here a 3D variation of electric field is produced. The first published work in ECVT with layering concept of sensor to bring about axial and radial variation of electric field was of Warsito and Fan [13].

ECVT sensors have the advantage of sensing irregular spaced geometries, low cost, Applicable to geometries of various sizes. The sensor geometry, shape, layers and number of channels for particular application has to be optimized and employed. Different applications have employed different type of 3D sensors to investigate the process. Studies have shown that 3 plane shifted sensor design is one among several viable sensor designs, which has been experimentally tested over hundreds of designs conducted [13, 15]. The reason for choosing such a multi layered shifted plane sensor design for 3D imaging is to increase the axial resolution and to reduce the degree of ill posedness of capacitance volume tomography [15].

Multi-layer shifted plane sensor configurations are used to image process under cylindrical pipes with pipe diameter ranging from 1 to 12 inch diameter pipes. Vessels with much higher diameters employ single layer configurations, as a triple-layer sensor design may cause radial accuracy problems due to the small length/diameter ratio for the sensing domain of such a 60-in ID vessel. Thus more electrodes with a single layer are employed to image vessels of bigger dimensions. Flexibility of ECVT sensor design employing a 90 degree bent to image gas-solid flows at the exit of a CFB riser [23].

ECVT is employed to study soil water infiltration [24], where hexagonal type sensors are employed with 32 electrodes distributed in 4 layers. Thus, Sensor configuration and design for ECVT needed to consider the process under investigation, vessel/pipeline dimensions, the information sought from the process. The sensor sensitivities for few sensor geometries are outlined by Warsito et al [13], where three layers cylindrical shifted sensors provide much better axial and radial resolution when compared to single layer and two layers cylindrical sensors. Planar sensors provide good radial resolution (decreases away from sensor) and poor axial resolution. Axial and radial resolution for other sensors is dependent on sensor geometries.

4. Sensor front end electronics and noise affecting performance

Sensor front end electronics for Electrical Capacitance Volume Tomography (ECVT) includes the metallic electrodes mounted around the pipeline/ vessel under investigation and electrical scheme for sensing the respective capacitances. A multi layered sensor arrangement is proposed by Warsito et al [13] to produce distinct electric field variation in both axial and radial directions.

ECVT works on the same principle as ECT. However, the axial and radial electric field/variation is considered for the former while the latter works on radial electric field variations. While designing the sensor and sensor front electronics, the inter electrode capacitance should be immune from external electromagnetic interferences such as 50/100Hz from power supplies. [10].

Apart from being immune to stray capacitances and noises, ECVT sensor should have a sufficient measurement resolution and data acquisition rates. Warsito et al [25] have developed a 32 channel Data Acquisition circuitry with a resolution of .21fF-.42fF and data capture rates of 4 frames/second for 32 channels ECVT. The DAQ system developed by



Process Tomography Ltd (UK), for is capable of capturing image data up to 80 frames per second [26]. Some other works such as listed in reference [24] have employed DAQ system developed from CTECH labs, (Edwar Technology Co., Tangerang, Indonesia) and is capable of capturing image data up to 496 independent measurements per 0.25 s. Stray immune sensor front end with a wide dynamic range in measurement and faster data acquisition systems applicable to processes with dynamic fast changing phase profiles is still under research [15].

4.1 Effect of Stray Capacitances and techniques to limit the effect of external EM interferences

ECVT faces a challenge for capacitance measurements. The front end transducer, DAQs are to be designed to provide high sensitivity and resolution for measuring small changes in capacitance [25]. For ECVT system, literature has cited three main sources of stray capacitances. These are, (1) sensor cables connected to the data-acquisition system (about 100pF for 1m cable); (2) ON/Off state capacitance of CMOS switches used for selecting the inter electrodes for capacitance measurements (about 3-8pF); (3) external shielding around the sensor [25].

Works have been published to mount the measurement circuitry directly onto the electrodes, thereby reducing the stray capacitance effect of the cable wires connecting to DAQs [27]. Integrated electrodes in ECT has reduced the stray capacitance by 100pF and thus the switching frequency employed could be increased up to 4MHz. Panji et al., (2014) [28] have developed an integrated DAQ and data processing system for ECVT application, where image reconstruction is done in parallel.

Electrodes are to be properly designed to limit the electric field within the sensing domain and to improve measuring sensitivity. External earthed screen, screening fins and axial guard electrodes had been employed. Axial guard electrodes are used to reduce the components of the capacitances between electrodes due to field paths outside the tube wall. External radial screens are employed to keep out external noise and to prevent the excitation signals from causing electromagnetic interference to other equipment [8].

An essential requirement of the system is that it should be insensitive to stray capacitances between the measuring electrodes and earth. Spatial resolution of ECVT depends on the number of electrodes mounted for sensing. Increasing the number of electrodes decreases the SNR of the system. A typical ECVT system should have a resolving measurement of .21 - .42fF [25]. The ECVT should be able to measure the small change in capacitance measurement in presence of stray capacitance of 50-150pF. The stray capacitance could change depending on the ambient temperature of operation and Structure of ECVT sensors, process vessels, etc.

As early 1988, HUANG et al [10] has proposed two stray immune capacitance measurement schemes. These are AC based circuits, and the switched-capacitor charge transfer circuit. The switched capacitor based scheme allows faster data capture rates with switching frequency up to 4MHz [27]. The switched capacitance scheme can suppress the stray capacitance effect it has a simple structure and cost effective. Baseline drift, charge injection effect and flicker noise affects the performance of the switched capacitance circuitry [29]. The AC based technique employs a continuous signal and has the advantage of high signal to noise ratio and low base line drift. However, the circuit is limited by the cumbersome structure and data capture speed. Most of the works on ECT and ECVT has employed switched capacitance circuitry for its faster data capture rate and simple construction.

4.2 AC based stray immune capacitance to voltage converter

The AC based scheme is accepted for its high accuracy. However, due to its characteristics analog device the data-acquisition rate is low and is about 150 frames/second for ECT. The main constraint is the relatively long settling time of the frequency dependent components of the filters and demodulators [30].

In 2005, studies conducted at Institute of Electrical Measurement and Measurement Signal Processing, Graz University of Technology, Austria by Hannes et al [31] has proposed a low-impedance front end circuitry to reduce the effect of stray capacitance. The authors have shown that low impedance circuitry is less affected by EM interferences. It shows a better signal to noise ratio, resulting in higher resolution for low impedance circuitry when compared to high impedance circuitry.

In 2007, works of Yan li et al in [32], have developed an AC based integrated circuitry to eliminate lead and stray capacitances. The authors have obtained a repeatability error of 0.281% and measurement drift of 0.05% per hour in capacitance measurements.

Huaxiang wang et al (2008) [30] have shown that the relatively narrow band width and long settling time of analog devices places limit in both data acquisition rate and measurement precision. They've employed FPGA based DAQ and implemented signal conditioning and acquisition functions in digital rather than in analog hardware to overcome the long settling time of the analog devices. Their result shows a Signal-noise ratio of 76dB is obtained. The Phase Sensitive Detectors (PSD) possesses long settling times. The long settling times reduced the data capture rate. A method to shorten the settling times of the low pass filter is to increase the cut – off frequency, thereby compromise on the Signal to noise ratio. The authors have implemented Digital Signal processing in FPGA modules for faster acquisition. They've obtained an acquisition rate of 150 frames/second online.

In 2010, D.styra and L.babout [33] have taken steps to eliminate the influence of Switch capacitances in OFF mode. They have pointed out that when the input measurement is less than OFF mode switch capacitance (CSW), output



measurement goes into saturation due to the CSW coupling. Nonlinear distortions appear because of signal saturation, temperature increases and hardware become instable.

In 2011, Zhaoyan Fan et Robert X. (2011) Gao have proposed a multiple excitation capacitance polling method (MECaP) [34] to improve the data capture rate for AC based technique. The authors have grouped the electrodes and measurements are taken. The improvement in resolution is obtained without changing the signal to noise ratio. As a result, a system employing MECaP with 'M' electrodes will only require 'M-1' capacitance measurements instead of $\frac{M(M-1)}{2}$.

Thus the acquisition speed is increased by M/2 times. The method will provide significant improvement in data capture rates for the large number of electrodes. The experimental study conducted by the authors on an 8 electrode ECT sensor has revealed an increase in scanning speed by 155% when compared with the traditional method.

4.3 Switched Capacitance charge/discharge based stray immune capacitance

Beck et al. 1989 have proposed a switched capacitance based circuitry [35]. Switched capacitance (SC) based charge/discharge front end sensor is seen to be employed for ECVT and ECT applications widely in literature. The charge transfer circuit can provide switching frequency of 2-4MHz. It can provide faster data capture rates, and due to its simple circuitry, parallel measurements can be used without the substantial increase in cost and complexity [35].

In 1992, an improved version of the SC measuring circuit was proposed by beck et al [10], where a differential output capacitance measuring circuit is employed. The measurement plates are switched between source and ground with a switching frequency f . The differential method has two advantages.

- 1) The sensitivity has doubled.
- 2) The output offset voltages tend to cancel each other provided that CMOS switches are similar in construction and characteristics.

The authors have revealed that even though the differential measuring scheme reduces the offset voltage, 20-30% of its effect is still observed. In 1998, Williams et al [27] have employed the differential measurement scheme with integrated electrodes to reduce the effect of stray capacitance of the connecting leads, thereby a reduction of 100pF of stray capacitance is observed. The authors have shown by reducing the stray capacitance to 50pF, the circuit could be operated with 4MHZ switching frequency, thereby increase the data capture rate of the system.

Around the early 2005 works have been implemented to scale down ECT system to sub-milli meter range [36]. In order to reduce stray capacitance a custom silicon integrated scheme is employed. The circuitry is based on a charge-transfer circuit and is implemented as a custom CMOS integrated circuit that is mounted close to the electrodes to reduce parasitic capacitance.

Warsito et al., 2011 [25] have employed a supply voltage of 10V for ECVT applications. Works on ECT related to medical imaging [9] have shown that a supply voltage of at least 10V or above is needed for sufficient capacitance measurements, else noise dominates the measurements. Jie Cui and P. K. Chan (2011) [29] have implemented correlated double sampling technique to limit the effect of flicker noise and developed a capacitance measuring circuit able to work at lower supply voltage of 3Vs.

5. ECVT - Sensor Performance

The sensor performance of ECVT is primarily determined by the capability of the sensor to distribute the electric field in axial and radial directions. Apart from distribution of electric fields in different direction, the performance of the sensor is also affected by environmental effects, such as temperature induced measurement drifts [37]. Performance of ECVT sensors in regard to temporal resolution, safety and cost has put ECT and ECVT for imaging opaque processes above other techniques. Multi layered electrode arrangement with different geometries [38] are introduced to enhance the special resolution of ECVT arrangements. Methods such as multiple excitation capacitance polling (MECaP) methods are introduced to enhance the spatial resolution without reducing signal to noise ratio [34].

After Warsito and Fan [13] showed the possibility of 3D imaging from layering concept of sensor arrangement, works have been undertaken to image gas-solid fluidized beds (Warsito et al, 2007) [13], velocimetry studies (Qussai. M, 2007) [11], to validate ECVT sensor performance with other techniques such MRI, optical protested for multi-phase flows (Qussai. M, 2009) [15], to design optimal sensor arrangement/geometry with radial and axial distribution of electric fields (Warsito et al in 2011) [25], and to test the performance of hexagonal shaped ECVT sensors for soil-water infiltration imaging (M. Mukhlisin et al, 2012) [24].

In 2007, Warsito et al have applied ECVT to study gas-solid fluidized bed system of 0.1m 1D. The authors have illustrated the interior flow structures (dynamic bed expansion, void breakage and movement) as 3D images obtained from ECVT system [39]. The experimental setup, procedures and materials employed were described by the authors [39]. A 12 electrode shifted 3 plane sensor arrangement were employed by the authors. The authors have claimed the 3D image obtained is in consistent with quasi 3D image obtained by ECT technique [26, 39]. The image obtained is also in consistent with the X-ray photo graph obtained of bubble in gas-solid fluidized bed with crushable coal particles. The authors have given a quantitative description of ECVT, ECT and optical probe performance in a 0.1m 1D gas-solid fluidized bed for FCC particles in both bubbling and turbulent regime. The results have shown that there is a small



difference in measurements between the ECVT and other two techniques. This difference is attributed to the low spatial resolution of ECVT. ECVT has been applied for velocimetry studies [11] for multi-phase flows.

Mark. A. Nurge, in 2007 has conducted studies ECVT with cuboids sensor geometry [37]. The author has investigated the effects of environment on the sensor performance. Results have revealed noise rms level of 1.5fF. The majority of the noise is added due to the external switch circuitry and cabling. Author has shown that temperature is one of the causes of capacitance drift. Capacitance change is also attributed to shifts in moisture content of the air.

In 2011, Marlin et al [38], have conducted studies to design and simulate the performance of different sensor arrangement for ECVT applications. As ECVT works with the distribution of electric fields in both radial and axial directions, Warsito et al had simulated the performance of 4 geometrical arrangement of electrodes namely, a) Rectangular, b) Hexagonal, c) Trapezoidal & d) triangular. Commercially available finite element solver Comsol multiphysics V3.4, was employed to obtain the electric field distribution. Hexagonal sensors provided more distribution of electric fields in the axial direction when compared to other geometries. Hexagonal ECVT sensors were employed in the study of soil water infiltration [24].

5.1 ECVT for medical application

Apart from industrial applications, ECVT is used to detect Breast cancer, brain tumour and to image brain activity [40-43]. A combination of triangular, rectangular and hexagonal shaped sensors are employed for such purposes.

W.P. Taruno et al have employed a combination of rectangular and triangular sensors for breast cancer detection [40]. The sensor employs the fact, that the cancerous breast cells have a higher permittivity when compared to healthy breast tissues. Study was conducted using actual phantom experiment where a paraffin wax ($\epsilon_r = 1$), imitates human breasts and a rubber ball ($\epsilon_r = 80$), imitates cancer cells. The results were compared with simulation experiments conducted using consoles multiphysics. Both the simulation and experimental procedures could reconstruct the malignant cancerous cells. They also have proposed that ECVT has the advantage of functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) in terms of spatial and temporal resolution respectively [41]. They've employed hexagonal sensors to detect brain activity. Neural activities were noted for 3 activities namely, 1) movement of left and right hands 2) Reading a book for 10mins. Comsol Multiphysics was employed for simulation studies and ILBP algorithms were employed for image reconstruction. The authors have reconstructed brain activity for the above mentioned procedures.

ECVT has been applied for brain tumour studies [42] where an abnormal electrical activity around the tumour infected area is detected. The system was experimented with patients suffering from ependymoma, oligodendroglioma, cranio-pharyngioma, germinoma pineal, and cerebellopontine angle tumours. The study showed positive correlation with MRI and CT results.

ECVT is applied for brain activity detection during executed and imagined movements [43]. Measurements were obtained on human subjects during different executed and imagined movements. Both the techniques showed that ECVT provides a complementary technique for brain activity studies.

6. ECVT-image reconstruction

Electrical Capacitance Volume tomography (ECVT) employs to generate simultaneous volumetric information of dielectric distribution inside the sensing domain. ECVT belongs to the soft field category of tomography techniques where the interrogating electric fields are dependent on the dielectric distribution of the imaging domain. Capacitance tomography has seen wide interest in research due to its non-intrusive, non-invasiveness, better temporal resolution, low cost, and flexibility for use in different vessels and safety for operating personnel. The image reconstruction in ECVT is an inverse problem to estimate the volumetric dielectric distribution from the capacitance data measured. The Capacitance between inter electrodes is given by equation (2).

Equation 2 relates the dielectric distribution to the capacitance. ΔV_{ij} is the voltage applied between electrode pair i, j .

The solution to the forward problem for ECVT is generally solved by, Linearization techniques [24] and Finite-element methods [14]. Linearization technique is less time consuming compared to FEM when employed with Iterative algorithms. Most of the image reconstruction works in ECVT has employed Linear Back projection and Optimization based Algorithms [13]. Soleimani et al has employed a temporal based image reconstruction based on correlation of a set of 3D image frames in time [14]. The three techniques are briefly described below.

6.1 Linear back projection technique

In linearization technique, the nonlinear relationship between capacitance measurements and dielectric distribution is linearized based on the sensitivity model. Here the entire imaging domain is divided into Voxels of known dimensions. The linearization technique could be summed up as, the response of the sensor due to arbitrary arrangement of dielectric distribution, could be obtained as the sum of the individual response, when each voxel has the dielectric in it. Based on the sensitivity model, the capacitance ' C ' in relation can be rewritten as [37].

$$C = SG \quad (3)$$

where S is calculated using the relation given below



$$S_{i,j} = \frac{E_i(x,y,z) \cdot E_j(x,y,z)}{V_i \cdot V_j} \quad i \neq j. \tag{4}$$

$S_{i,j}$ is the sensitivity distribution of the electrode pair i, j . $E_i(x, y, z)$ is the electric field distribution when i th electrode is excited with voltage V_i and all others are grounded. Similarly $E_j(x, y, z)$ is the electric field distribution when j th electrode is excited with voltage V_j and all others are grounded. C is the M dimensional capacitance vector. G is the N dimensional image vector; M is the number of electrode pair combinations and N is the number of voxels in the imaging domain, the sensitivity matrix has the dimension $M \times N$. The reconstruction problem consists of estimating the image vector ' G '. As the sensitivity matrix is ill posed due to fewer numbers of measurements when compared to the number of voxels. The sensitivity matrix cannot be inverted. Thus image vector is obtained by back linear back projection (LBP) [12], i.e.

$$G = S' C \tag{5}$$

An iterative procedure is employed to obtain an accurate image. The iterative procedure aims to estimate the image vector from the capacitance measurements such that difference between the estimated capacitance from image vector and true capacitance is minimum, i.e. $\|C - SG\|$ is below an acceptable value. Iterative algorithms are generally classified as algebraic reconstruction and optimization based reconstruction technique [12]. Iterative algorithm is described in Eq 6.

$$G^{k+1} = G^k + \beta^k S^T (C^m - y(G^k)) \tag{6}$$

K , is the iteration number, β^k is the relaxation factor if k th iteration. C^m is the measured capacitance and $y(G^k)$ image estimate vector G . Iterative algorithms differ mainly in the selection of relaxation parameter. Widely used iterative method is land Weber technique. The iteration procedure of ILBP is given as [39].

$$G^{k+1} = G^k - \alpha^k S^T (SG^k - C) \tag{7}$$

The back projection technique requires less computational time, but it introduces image artefacts [37].

6.2 Optimization technique

In optimization technique for ECVT application, a set of predefined objective functions are iteratively optimized to yield a more probable image [44]. The optimization technique aims to find an image vector that simultaneously minimizes four objective functions, namely

- 1) Negative entropy function.
- 2) Least square errors
- 3) Smoothness and small peakedness function.
- 4) 3-2D matching functions.

The negative entropy objective function is defined as

$$h_1(G) = \gamma_1 \delta_1 G \ln(G), \quad \delta_1 = \begin{cases} 1, & \text{if } G_j > 0 \\ 0, & \text{if } G_j = 0 \end{cases} \tag{8}$$

γ_1 is a normalized constant between 0 and 1. The least square error of the capacitance measurement is given as

$$h_2(G) = .5\gamma_2 \|SG - C\|^2 \tag{9}$$

γ_2 is the normalized constant between 0 and 1 and S is the 3D sensitivity matrix, calculated based on Eq 3. The smoothness and small Preakness function is defined as

$$h_3(G) = .5\gamma_3 (G^T XG + G^T G) \tag{10}$$

γ_3 is a normalized constant between 0 and 1 and X is an $N \times N$ non uniformity matrix. N is the number of voxels in the imaging domain. The additional objective function is required for 3D image reconstruction and is defined as

$$h_4(G) = 0.5\gamma_4 \|H_{2D}G - G_{2D}\|^2 \tag{11}$$



H_{2D} Is the projection matrix from 3D into 2D having dimensions $N \times N_{2D}$. N_{2D} is the number of voxels in one layer of 3D volume image vector and γ_4 is a normalized constant between 0 and 1. A Neural Network based Multi objective Optimization image reconstruction technique have been described by Qussai. M (2006) [12].

6.3 Regularization Techniques

Regularization techniques are employed so as to make the non-invertible Sensitivity Matrix 'S', invertible for Image reconstruction. The image vector is produced by adding a regularization parameter. To illustrate the method consider the forward equation in the linear sensitivity model rewritten as below.

$$S' SG = S' C \tag{13}$$

$$G = (S' S)^{-1} S' C \tag{14}$$

$(S' S)$ is not invertible and hence a regularization parameter μ is added to make the matrix invertible.

Thus

$$G = (S' S - \mu I)^{-1} S' C \tag{15}$$

where μ is the regularization parameter and I is the identity matrix. The quality of reconstructed image depends on the regularization parameter. Soleimani et al [14] has employed a Temporal image reconstruction based on inter frame correlation of adjacent frames. The technique employs a set of data frames in time 't' for image reconstruction. The forward problem in temporal image reconstruction technique is expressed as

$$C^t = S^t \varepsilon^t + n^t \tag{16}$$

where C^t is the normalized concatenated capacitance measurement data, $C^t = \{C_{-d}^t + \dots + C_{0..}^t + C_d^t\}$,

ε^t is the corresponding relative permittivity, $\varepsilon^t = \{\varepsilon_{-d}^t + \dots + \varepsilon_0^t + \dots + \varepsilon_d^t\}$. Eqn is re written in matrix form as

$$\begin{bmatrix} C_{-d}^t \\ \vdots \\ C_d^t \end{bmatrix} = \begin{bmatrix} S & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & S \end{bmatrix} \begin{bmatrix} \varepsilon_{-d}^t \\ \vdots \\ \varepsilon_d^t \end{bmatrix} \tag{17}$$

$C_{-d}^t, \dots, C_{0..}^t, C_d^t$ are the capacitance measurement set taken at different time intervals. The technique employs a set of 3D image data frames to create a 4D image. The inverse procedure consists of inverting the Concatenated Sensitivity matrix with the help of regularization parameter and estimating the image vector at times 't'. The temporal 4D image reconstruction method has been described by Soleimani et al (2009) [14].

6.4 Performance of ECVT image reconstruction

The Qualitative performance of linear back projection (LBP), Land Weber Back Projection (ILBP), and Optimization based algorithm (MOIRT) are presented by Qussai. M. [12] and the performance of the temporal based image reconstruction is given by Soleimani et al [14]. Quassai. M has employed two sensor geometries, one of the rectangular and other of triangular sensor.

The triangular sensor produced an elongation of the image in the axial direction. The performance of NN-MOIRT algorithm is much satisfactory when compared to LBP and ILBP. Elongation of the image is also observed for triangular sensor with NN-MOIRT algorithm. Experiments conducted to image moving objects showed distortion with ILBP algorithm, whereas NN-MOIRT gives accurate images. This brings out that NN-MOIRT can give better performance when compared to ILBP for moving objects and can overcome sensitivity induced artifacts in the image. The NN-MOIRT has been used in imaging multiphase flows [15], for cylindrical and other complex geometries. Warsito et al (2012) [39-40] have employed ILBP to image breast cancer tissues and to image brain activity. The Temporal image reconstruction presented by Soleimani et al [14], is 4D imaging technique to image moving objects. The Algorithm has given better noise performance. The Algorithm was tested with 2, 4 and 6% added noise and the reconstructed image showed better noise performance.

7. Conclusion

Progress in the field of Electrical Capacitance Volume tomography has been summarized in the article. ECVT employs 3D capacitance sensor where the electric field is distributed in axial and radial direction for 3D imaging. Sensor shape and configurations play an important role in ECVT performance. Optimal sensors has been employed for a particular application for better performance. ECVT has wide applications in industrial and medical process imaging. Flexibility of ECVT sensors to accommodate various geometries enhanced its applications to complicated vessels / processes. Optimal Sensor design, robust image Reconstruction Algorithms, Sensor electronics and data acquisition with the high signal-noise ratio are the key factors that determine the performance of a typical ECVT system.



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Author' biography with Photo

Dr. Aljohani has completed his PhD from the Georgia Institute of Technology, USA in 1996. He is currently the chairman of the Department of Nuclear Engineering, King Abdulaziz University, Saudi Arabia and the director of the center for radiation protection and training. He works also as an adjunct professor at the Nuclear Engineering of the University of Missouri for Science and Technology, USA. He is also the Chairman of the Aramco's Non Destructive Testing Chair.

His field of research covers Reactor Physics, Reactor Thermal-hydraulics, CFD, Radiation Detection and Measurement, Nuclear Desalination, Nuclear Electronics, Computed Tomography, Radioactive Particle Tracking, Data Acquisition System Design and Monte Carlo Simulation. He has developed and designed more than 70 innovative hardware and software systems.

Mohammed S. Aljohani; PhD

Chairman; Department of Nuclear Engineering

Director; Radiation Protection and Training Center

Chairman; Saudi Aramco Non-Destructive Testing Chair

KAU, P. O. Box 80204, Jeddah 21589 Saudi Arabia

Adjunct Professor; Nuclear Engineering, Missouri University for Science and Technology, MI, USA

Office: +966 2 695 2276

Fax: +966 2 695 2648

Mobile:+966 (0) 590 533 225

