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SIMULATION OF ELECTRODE FOR DUAL-MODALITY ELECTRICAL RESISTANCE TOMOGRAPHY AND ULTRASONIC TRANSMISSION TOMOGRAPHY FOR IMAGING TWO-PHASE LIQUID AND GAS

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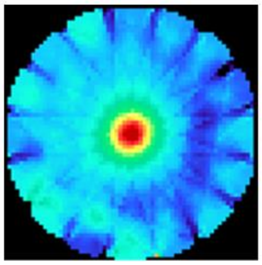
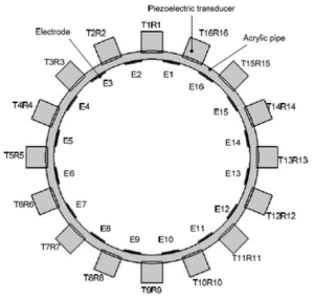
Graphical abstract



Abstract

Accurate multiphase flow measurement of gas/liquid, liquid/solid and liquid/liquid flow is still challenging for researchers in process tomography. The reconstructed images are poor particularly in the center area because of ill-posed inverse problems and limited of measurements data. Dual-modality tomography has been introduced to overcome the problem by means each modality is sensitive to specific properties of materials to be imaged. This paper proposed combination of ultrasonic transmission tomography (UTT) and electrical resistance tomography (ERT) for imaging two phase gas/liquid. In the proposed combination, detection ability in the medium of interest improved because two different images in the same space can be obtained simultaneously. This paper presents 3D numerical modeling approach using COMSOL software for ERT excitation strategy and electrode pre-designed geometry. Electrical resistance tomography (ERT) can be implemented for gas/liquid flow if the liquid is conductive. The objectives of this work is to analyze the optimum electrode dimension and shape in order to improve the situation of: (1) gas bubble detection located in the centre of the medium, (2) potential distribution and current density in a conductive medium, the developed numerical model simulated the changes in resistivity of the conductive material, with variations of electrode sizes, with opposite current excitation implemented into the region of interest. Simulation results show that the electrode size of 12 mm (w) × 40 mm (h) is suitable, which gives a good detection of center gas bubble with diameter 10mm in 100-mm-diameter acrylic vessel. Finally the findings are verified with Image reconstruction using Linear Back Projection (LBP) which gives good indication of the 10mm gas bubble.



Keywords: Dual-modality tomography, Electrical resistance tomography, ultrasonic tomography, opposite excitation, time-of-flight (toF)

1.0 INTRODUCTION

Tomography had been used in process industry for several decades. Tomographic imaging of multi-component including gas/solids, gas/liquid, and liquid/liquid in pipe flows provides useful information about flow characteristics. In Tomography systems, the physical properties of a material distribution can be described by either permittivity or conductivity properties. A tomogram image of the phase interactions is important to understand the operation of multi-phase flows. The image is provided by different measurement techniques with quantitative local and global dynamic information of the flow that is useful for system design and control[1]. As an on-line measuring technique possessing advantages of visualization, low-cost, non-invasive and robust tomography has become an accepted measuring technique in process applications. Tomography instrument is gaining more attention not only be used in process application but in laboratory facilities as well. Most of conventional flow-meters can be used on single-component flows, whereas others can be utilized in multi-component flows provided that there is information on how the components are mixed how they flow with relation to each other. This characteristic is important in process control system, in which the amount and accuracy of the feedback information are crucial for the stability of the closed loops [2].

In many cases physical quantities could not be described by either permittivity or conductivity but a combination of both permittivity and conductivity[3]. Therefore often a flow cannot be measured by single tomography system. In some applications, single-modality process tomography systems had been used for decades and proven to give sufficient information for some applications. However in other applications, such as three-phase flow, additional information is required. In fact, many industrial processes are complex and contain multiple components, which require multiple measurement techniques to individually quantify them. To facilitate this process, a multi-modal process tomography system must allow individual modality data to be collected and combined effectively[4].

A multimodality tomographic system is defined as one in which two or more different sensing modalities are used to locate or measure different constituents in the object space [5].The systems provide component specificity by using independent component sensing in the measurement volume, by electrical properties such as capacitance and gamma-ray sensing in oil/water/gas tomography. In single modality tomography system, ERT is used to visualize the conductivity distribution of the medium to be imaged and ultrasonic transmission tomography (UTT) is used to distinguish medium boundaries based upon interactions between the incident ultrasonic waves and objects to be imaged [6]. UTT has the benefit of detecting edges accurately, while it is not possible to reconstruct permittivity values of the materials involved. In contrast ERT with nonlinear iterative reconstruction enables the quantification in terms of absolute conductivity values. However, due to needful of regularization, no sharp edges can be resolved. Because of the complementary properties from these modalities, it is possible to combine the ERT and UTT to produce dual-modality tomography sensor. The proposed system the ERT can be used to visualize the conductive component and UTT can be used to visualize the boundaries medium of interest.

Rectangular shaped electrodes are initially selected for the simulation study. In the simulation, optimized rectangular electrodes array were put forward together in a single plane with the ultrasonic transducers. Authors developed a three-dimensional ERT/UTT model using finite element method (FEM) with COMSOL software. A 3D numerical analysis was developed using COMSOL and the authors analyzed the influence of width and length of electrodes with presence of gas bubble in the distribution of the sensing field. The geometry of the ERT electrodes were simulated and presented in the presence of acoustics wave at frequency 328 kHz propagated into the medium.

2.0 THEORITICAL BACKGROUND

Multi-modal systems inherently encourage a systematic approach in contrast to current generation process tomography systems that are complex, expensive and designed primarily for the prototype laboratory. A successful system must allow individual sensor data to be collected and combined effectively. It must therefore exploit opportunities for rationalization and sharing of resources, and deal with hazards of mutual interference [7]. The proposed system is based on the use of two types of sensing elements which consists of 16 electrodes of ERT and 16 ultrasonic transceivers located externally respectively in an axial distance around the circumference of an acrylic pipe which are shown in Figure 1

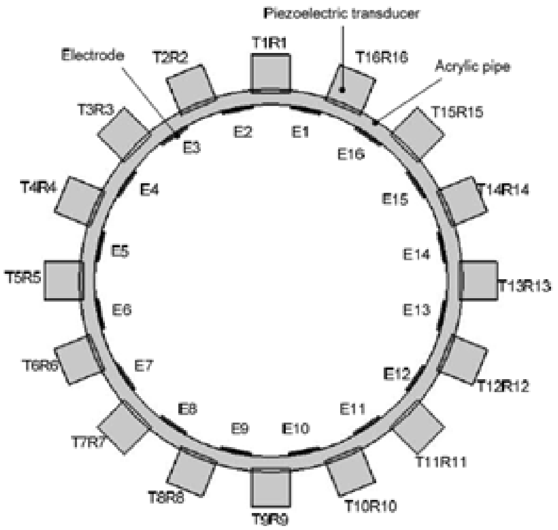


Figure 1 Cross section of the dual-modality ERT/UTT tomography system

2.1 Electrical Resistance Tomography

Electrical resistance tomography (ERT) is a particular case of electrical impedance tomography (EIT). ERT is most widely and easily implemented for purely resistive medium [8]. Differences in electrical properties are the basic principle of ERT. In ERT, an electrical current is injected through a set of electrodes placed in a boundary of the domain of interest, which results in an electrical field that is conditional on the conductivity distribution within the domain. The resulting electrical potential at the domain parameter can be measured using the remaining electrodes. The potential value, measured at the electrode, is the sum of the potential on the surface under the electrode and the voltage drop on the contact resistance of the electrode:

$$u + Z_l \sigma \frac{\partial u}{\partial \bar{n}} = U_l ; l = 1,2,3..L \qquad (1)$$

where L is the number of electrodes, u is defined as electric potential distribution in the medium, σ is the conductivity of the medium, is surface under l-th electrode, $\bar{n}$ is an outward unit normal, Z is the effective contact impedance between l-th electrode and U is the fluid and potential at the l-th electrode.

2.2 Ultrasonic Transmission Tomography

Ultrasonic sensors have been successfully applied in processes, particularly in flow measurement[9]. Ultrasonic sensor systems are based upon interactions between the incident ultrasonic waves and the object to be imaged. It is applicable only to a process where a significant interaction occurs[5]. Previous research has been carried out in multiphase flow measurements which give promising results using ultrasonic sensors [10]. The interaction of ultrasound with a material can be represented by its acoustic impedance, which can be described as:

$$Z = \rho c \qquad (2)$$

Where c is the velocity of sound in the medium (m/s), Z is the acoustic impedance (kg/m^{2}s) , ρ is the medium density (kg/m^3).

Process tomography using ultrasonic sensing relies upon detectable interactions both in a homogeneous transmission medium and from interfaces, for example, at gas bubbles in a liquid. In process applications, a variety of intersections occur causing attenuation to incident waves owing to the presence of the object or field between the receivers and transmitters. It is clear that the greater the difference in impedance at the interface, the greater the amount of energy that will be reflected[11, 12]. The reflection and transmission coefficient can be formed into the following fractions[13] as:

Reflection coefficient, $R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$ (3)

Transmission coefficient, $T = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2} = 1 - R$ (4)

Where Z_1 is acoustics impedance of material 1 (kg/m^{2}s), Z_2 is acoustics impedance of material 2 (kg/m^{2}s)

3.0 SIMULATION

COMSOL Multiphysics is model based software, which solves both stationary and time-dependent partial differential equations (PDEs), by numerical techniques based on the finite element method. The COMSOL Multiphysics simulation software environment facilitates all steps in the modeling process - defining model geometry, meshing, specifying required physics, solving, and then visualizing results. The dual-modality model uses the 3D time-dependent analysis of electric current of the AC/DC module in COMSOL Multiphysics 4.2a software tool. The model consists of an acrylic cylinder with diameter of 110mm and height of 300 mm. The cylinder is filled with sea water with conductivity of 0.3 S/m. The boundary condition of the acrylic cylinder wall was set to electric insulation. The 16-electrodes functions as source, sink, reference, and measurement electrodes and they are modeled as conductors by considering equip-potential surfaces. The parameters and dimensions are shown in Table 1. New ERT electrode shape is implemented in the simulation which is illustrated in Figure 2.

Table 1 Parameters and dimensions

Parameter	Value
Inner diameter	100 mm
Outer diameter	110 mm
Pipe height	300 mm
Number of electrodes (N)	16
Electrode's height (h)	20-140 mm
Electrode's width (w)	2-12mm
Electrode's material	Stainless steel
Current excitation	10 mA; 100kHz
Gas bubble (radius)	5 mm
Number of ultrasonic transceivers	16
Frequency	328kHz
σ (sea water)	0.3 S/m

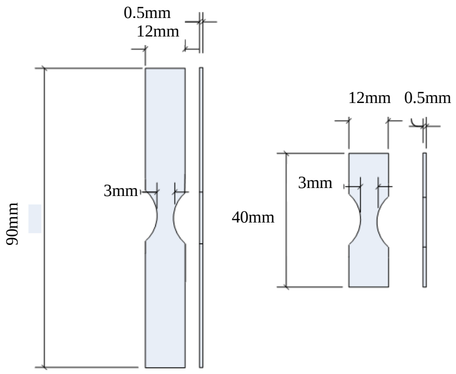
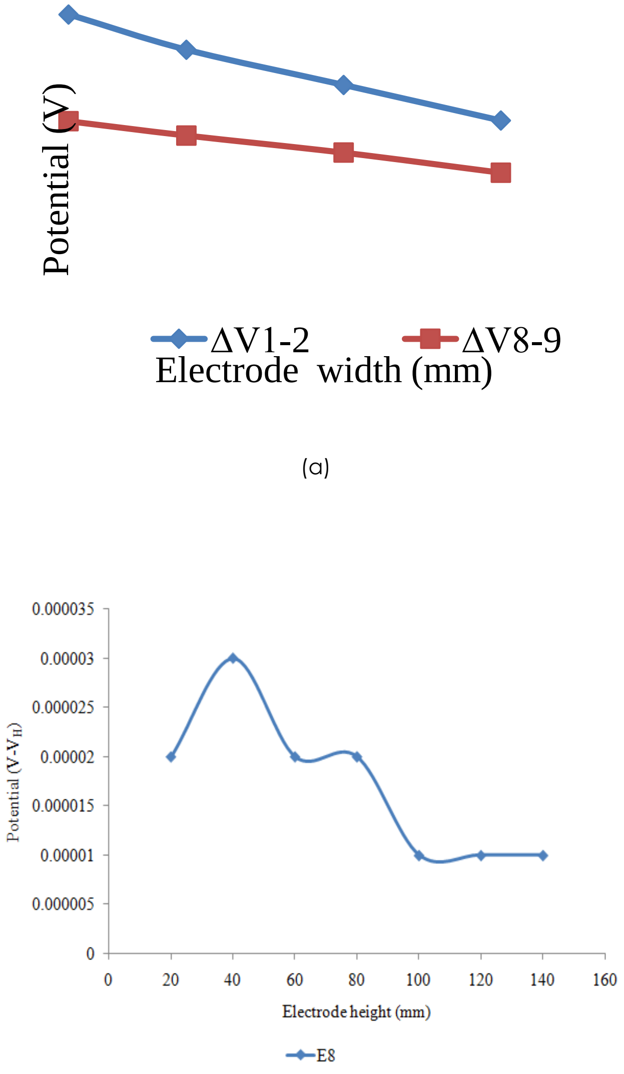


Figure 2 ERT Electrode 12mm ×40mm for dual-modality tomography system

4.0 RESULTS

Under the opposite excitation strategy, simulation has been carried out to compare surface potential of electrode heights between 20-140mm, from Figure 3(b) the 40mm electrode produces significant potential differences and improve significantly the axial parallel distribution of the sensing field compared with the other electrodes. In Figure 3(a) ERT electrodes with greater width reduce the pronounced potential near the excitation electrode and sink electrode which is the result of less current density near the excitation and sink electrode. Wide electrodes improve the evenness of the field distribution, which improves signal strength. It also improves the ability of object detection, particularly in the central region. In the proposed single-plane dual-modality tomography system, wider steel electrodes result in the reflection of ultrasonic waves during propagation in a cylindrical cell medium. Simulation results presented in Figure 4 shows 12 mm width rectangular electrodes cause reflection of some propagated waves and attenuate at the receiver.

However, with the opposite measurement strategy proposed by Pinheiro et.al [14]suggested that in order to obtain maximum value, the optimal size of the electrodes should cover 60% of the sensing area. From the results obtained in Figure 3(a) and (b), it is suggested that the suitable electrode width and height for the proposed system is 12 and 40 mm respectively.



(a)

(b)

Figure 3 (a) Surface potential at electrode 5 and 8 (E8) with electrode's width 2-12 (mm); (b) Surface potential with various electrode height (mm)

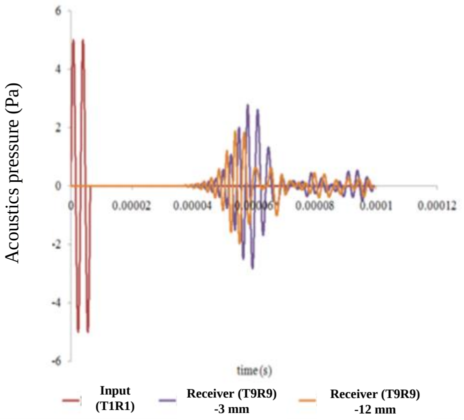


Figure 4 Received signal at transceiver (T9R9) for new electrode (3mm) and rectangular 12 mm electrode

The performance of the proposed electrode 12mm 40mm is further examined with a gas bubble with a radius of 10mm positioned at the center of the vessel. Two types of rectangular electrodes were simulated: 12mm×40mm and 12mm× 90mm . The surface potential measurements were taken with respect to the homogeneous medium for both sizes. The result is shown in Figure 5.

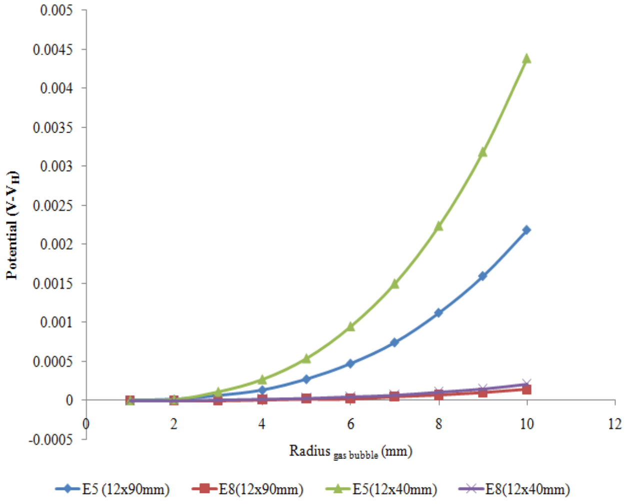


Figure 5 Comparison of centered gas bubble with multiple sizes between 12mm 40mm and 12mm 90mm

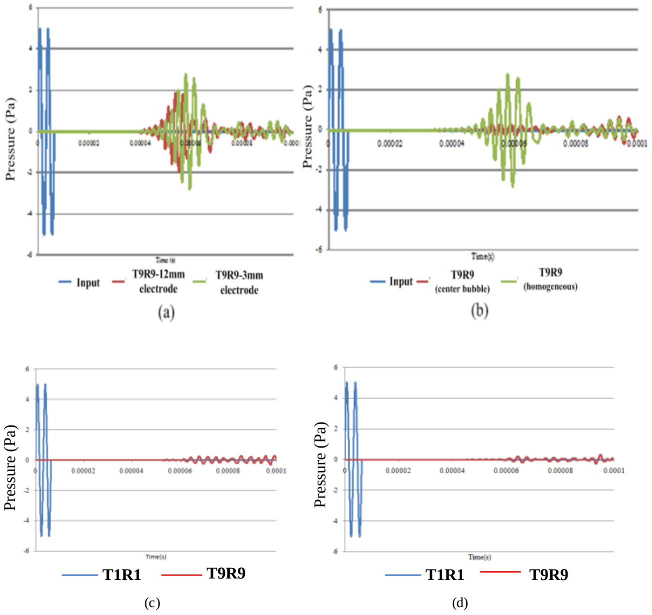
From the simulation results, the following observations can be made: The 40mm electrode produce better pronounced surface potential compared to the 90mm electrode. The surface potential is significant at radius higher than 4mm. The simulation also concluded that none of the electrodes produces significant surface potential at electrode 8 the farthest electrode.

In ultrasonic wave transmission it is essential to predict the amount of ultrasonic wave penetration through the medium of interest. The transmitted wave was given to the piezoelectric (PZT) transducer which selected as the transmitter, and the penetrated and reflected waves were detected by the PZTs which configured as the receiver. The first interaction occurs between the transducer and the wax, the second interaction is between the wax and the acrylic vessel section, the third interaction is between the acrylic vessel section and the liquid, the fourth interaction is between the liquid and the gas media and finally the interaction between the gas and liquid media. Assuming the ultrasonic energy losses between the transducer/ wax/ acrylic vessel are zero, the investigations of ultrasonic wave propagation of the proposed configuration is calculated in Table 2.

Table 2 Ultrasonic reflection and transmission coefficient between medium

Interaction	Reflection coefficient (%)	Transmission coefficient (%)
Acrylic/ liquid	36.17	63.83
Liquid/gas	99.94	0.06
Acrylic/Aluminum	68.17	31.83

From Table 2, it is found 86.33% of transmitted ultrasonic wave capable to penetrate the acrylic /liquid interface. This transmitted ultrasonic wave will be received by the opposite ultrasonic receivers and amplified to an appropriate level before the measurement is taken. However, in calculation with inclusion it is proved that due to large difference of acoustic impedance between the liquid and gas medium, therefore 98.50% of ultrasonic wave will be reflected at liquid/gas interface and scattered within the liquid in acrylic vessel. Less than 2% of transmitted ultrasonic wave capable to penetrate the liquid/gas interface. This concluded that approximately total reflection of ultrasonic wave at the liquid/gas interfaces. The residual ultrasonic wave is very small compared to the acoustic impedance at both gas/liquid interfaces and therefore it loses its energy during the next propagation[15]. This indicates transmitted ultrasonic wave is detectable if the transmission along the path is free from gas bubble and inversely the transmitted ultrasonic wave is totally reflected and it is not detectable if gas bubbles present in the transmission path. This is illustrated in Figure 6.



(a) (b) (c) (d)

Figure 6 Pulsed input pressure produced by 328kHz ultrasonic transducer (a) Homogeneous medium, (b) Center gas bubble, (c) Gas bubble near transmitter (T1R1), (d) Inclusion near receiver (T9R9)

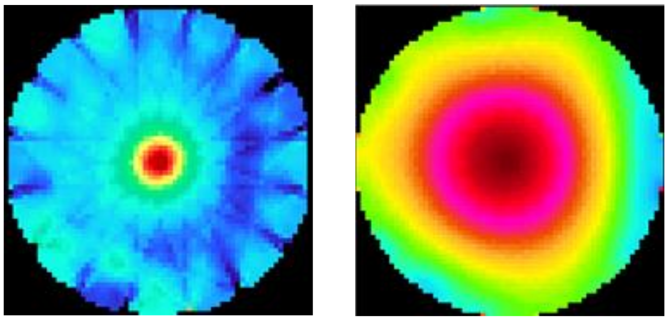


Figure 7 UTT and ERT Image reconstruction for centered gas bubble with Linear Back Projection (LBP)

5.0 DISCUSSION

From the results, it is possible to combine the electrical resistance and ultrasonic transmission at the same plane to improve the reconstruction images particularly for the central region. The simulation result indicates the ERT is capable to distinguish centre inclusion at several positions. However the sensitivity of the bubble located most distance from the source is still a challenge. The potential drop in ERT can be reduced and the signal strength can be improved by using wider and longer electrodes. However the electrode width must be carefully selected to avoid the signal reaches the asymptote level due to number of electrodes and shunting effects in ERT. UTT provides more useful information of bubble location which can be used as a priori information in the proposed system. The comparison between centre bubble images between UTT and ERT can be observed in Figure 7. Gas bubble located along the projection path acts as strong acoustics obstacles and attenuates the propagated waves. The new electrodes provide a better projection path and increase number of receivers as propagated waves are less reflected with acrylic/steel boundaries. The image reconstruction shown in Figure 7 indicates a centre gas bubble with 10mm diameter can be observed by the proposed system

6.0 CONCLUSION

In this paper, dual-modality tomography multi imaging system has been proposed using hard-field and soft-field technique. In the proposed system, the conductivity distribution object of interest using ERT is obtained by simulating the surface potential and the ultrasonic measurement using properties the time of flight of the transmission wave and acoustics impedance. The simulation results presented for the proposed system showed the information from UTT can be used as a priori information about bubble location in dual-modality UTT/ERT tomography system. Therefore future works will be directed towards the signal conditioning circuits and data acquisition system to verify the results in field conditions.

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