Jurnal
Teknologi

Full Paper

REVEALING THE UNSEEN: A BRIEF REVIEW OF INVASIVE AND NON-INVASIVE PROCESS TOMOGRAPHY IN INDUSTRY

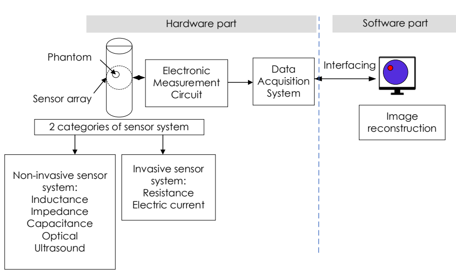
Ain Eazriena Che Man[a], Yasmin Abdul Wahab[a*], Nurhafizah Abu Talip Yusof[a,b], Suzanna Ridzuan Aw[c], Mohd Mawardi Saari[a], Ruzairi Abdul Rahim[d], Sia Yee Yu[e]

[a]Faculty of Electrical & Electronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[b]Centre for Research in Advanced Fluid & Processes (Fluid Centre), Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia
[c]Faculty of Engineering Technology (Electrical & Automation) University College TATI, 24000, Jalan Panchor, Telok Kalong, 24000 Kemaman, Terengganu, Malaysia
[d]Process Tomography Research Group (Protom-i), School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[e]LOGO Solution Sdn. Bhd., suite 0525, Level 5, Wisma SP Setia, Jalan Indah 15, Bukit Indah, 79100 Iskandar Puteri Johor Malaysia

Article history
Received
15 August 2024
Received in revised form
25 October 2024
Accepted
3 November 2024
Published Online
26 June 2025

*Corresponding author
yasmin@umpsa.edu.my

Graphical abstract



Abstract

In the field of multiphase flow characterisation, process tomography techniques have attracted a lot of attention because they provide important insights into the internal dynamics of complicated systems. In particular, non-invasive and invasive techniques are compared and several forms of process tomography utilized for multiphase regime identification are reviewed in this work, with an emphasis on industrial applications. Non-invasive process tomography methods evaluate electrical qualities or fluctuations in conductivity using external sensors or electrodes, allowing for real-time imaging and monitoring without physically altering the system. In contrast, more precise and localized measurements are made possible by invasive process tomography techniques, which entail the direct insertion of sensors or probes into the system. The comparative benefits and drawbacks of invasive and non-invasive process tomography methods for multiphase regime identification are also included in this review. It examines variables like measurement precision, spatial resolution, intrusiveness of the system, and installation needs. When choosing process tomography methods for finding multiphase regimes in industrial applications, researchers can make well-informed selections with the help of this review, which provides insights into the advantages and disadvantages of each methodology.

Keywords: Process tomography; dielectric medium; multiphase regimes; ECT; conducting pipe

Abstrak

Dalam bidang pencirian aliran berbilang fasa, teknik proses tomografi telah menarik banyak perhatian kerana ia memberikan pandangan penting tentang dinamik dalaman sistem yang rumit. Khususnya, teknik bukan invasif dan invasif dibandingkan dan beberapa bentuk tomografi proses yang digunakan untuk pengenalan rejim berbilang fasa disemak dalam kerja ini, dengan penekanan pada aplikasi industri. Kaedah proses tomografi bukan invasif menilai kualiti elektrik atau turun naik dalam kekonduksian menggunakan penderia atau elektrod luaran, membolehkan pengimejan dan pemantauan masa nyata tanpa mengubah sistem secara fizikal. Sebaliknya, pengukuran yang lebih tepat dan setempat dimungkinkan oleh teknik proses tomografi invasif, yang memerlukan pemasukan terus penderia atau probe ke dalam sistem. Faedah perbandingan dan kelemahan kaedah proses tomografi invasif dan bukan invasif untuk pengenalan rejim berbilang fasa juga disertakan dalam ulasan ini. Ia meneliti pembolehubah seperti ketepatan pengukuran, resolusi spatial, gangguan sistem dan keperluan pemasangan. Apabila memilih kaedah proses tomografi untuk mencari rejim berbilang fasa dalam aplikasi industri, penyelidik boleh membuat pilihan yang bermaklumat dengan bantuan semakan ini, yang memberikan pandangan tentang kelebihan dan kekurangan setiap metodologi.

Kata kunci: tomografi proses; medium dielektrik; rejim berbilang fasa; ECT; paip pengalir

1.0 INTRODUCTION

In the field of multiphase flow characterisation, process tomography has become an indispensable tool that offers priceless insights into the internal dynamics of complicated systems [1]. Tomography techniques provide improved industrial process monitoring, control, and optimization by producing comprehensive images of the interior structure and composition of processes [2]. These methods are widely used in many different industries, such as food processing, petrochemical, chemical, and pharmaceutical, where an understanding of multiphase flow behaviour is crucial to process efficiency and product quality[3].

Process tomography methods are often divided into two groups: invasive and non-invasive[4]. By inserting sensors or probes right into the process, invasive approaches enable highly precise and targeted measurements. Although these techniques can provide great spatial resolution and measurement precision, they are frequently linked to disadvantages like the possibility of process disturbance, complicated installation requirements, and restricted application in harsh or dangerous situations [5].

Non-invasive methods, on the other hand, record measurements without physically intervening in the process by using external sensors or electrodes. These techniques are beneficial because they need little interference, are simple to set up, and work well for real-time monitoring. On the other hand, when compared to their invasive equivalents, non-invasive procedures could have poorer measurement accuracy and spatial resolution. Furthermore, because non-invasive sensors monitor indirectly, it might be difficult to understand the data they collect [6].

There is an increasing need for a thorough comparison to help researchers and industry personnel choose the best approach for their particular applications, given the unique benefits and drawbacks of both invasive and non-invasive process tomography techniques. The objective of this review is to present a thorough examination of the several kinds of process tomography that are employed in multiphase regime identification, with an emphasis on the relative benefits and limitations of invasive versus non-invasive methods. This article aims to provide insights into the advantages and disadvantages of each approach by analysing various factors, including spatial resolution, measurement accuracy, intrusiveness of the system, and installation requirements. This will help in making well-informed decisions for future research and industrial applications.

2.0 OVERVIEW OF PROCESS TOMOGRAPHY

A non-destructive imaging method called process tomography is used to visualize and examine in real time the internal behaviour of industrial processes such fluid flow, mixing, and separation. Process tomography has been extensively employed in several industrial applications, such as chemical processing, oil and gas production, and pharmaceutical manufacture, according to J. Yao *et al.* [1]. According to H. Wu *et al.* [7], the method has also been used to investigate fluid flow and mixing in a variety of processes, including those involving multiphase flows and complex geometries.

It receives data from sensors positioned throughout a system and converts it into images that depict the insides or behaviour of the process [8]. Many different industries, such as chemical processing, oil and gas production, and pharmaceutical manufacture, use this adaptable and affordable technology extensively. It makes it possible to keep an eye on and improve processes like chemical reactions, multiphase flows, and fluidized beds. Process tomography can also be used in environmental monitoring to evaluate the flow of fluids or pollutants via soil or subterranean reservoirs. Various methods are used, each having pros and cons and based on different physical principles, depending on the particular application.

Process tomography, as illustrated in Figure 1, comprises two main parts: hardware and software. It also consists of three basic components: sensing systems, data processing methods, and process applications [9]. In sensing systems, multiple sensors are placed around the pipe or vessel and connected to measurement circuits to transmit and receive signals. The output signals were then conditioned by the data processing methods, also known as data acquisition systems (DAS), and given as input to a process application so that it could be reconstructed as a tomogram. The selection of the sensor, the sensing methods, and the image reconstruction algorithm are the three factors that, in general, might affect the tomogram's quality [9]. In the meantime, the hardware and facility and engineering approach optimization affect the regime's behaviour [10].

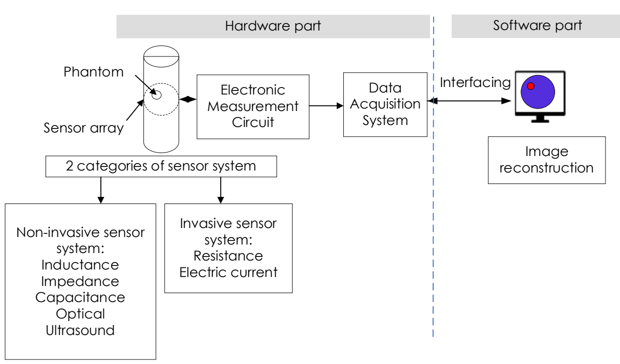


Figure 1 System configuration of process tomography

Two primary considerations are frequently researched while choosing sensors for multiphase regime visualization and monitoring. The diameters, percentages, and angles of the sensors comprise the initial set of parameters. The quantity of electrodes applied to the objects is the second. Selecting appropriate sensors can improve the sensitivity field in multiphase regimes, resulting in tomograms of superior quality [11]. Furthermore, the method of applying sensors to objects, known as sensing techniques, can impact the quality of tomograms [12]. Four categories of tomography sensing techniques: invasive, non-invasive, intrusive, and non-intrusive have been created over time. These four methods of sensing are shown in Figure 2.

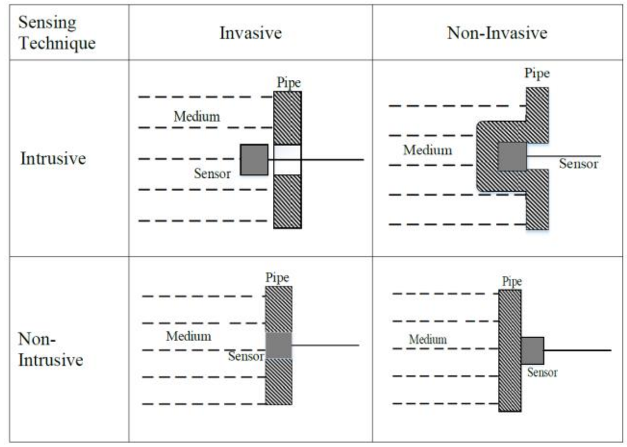


Figure 2 Types of sensing techniques [13]

Whether a sensor is invasive or non-invasive determines how it is configured. Non-invasive sensors are located externally, avoiding direct touch, whereas invasive sensors are in direct contact with the process flow. Non-intrusive sensors are installed outside the pipeline, with or without touch, while intrusive sensors are installed inside the pipeline and may or may not make contact with the flow. Every approach has advantages and disadvantages that vary based on the use. Moreover, process tomography frequently encounters difficulties because of its intrinsic complexity, which limit the usefulness of tomograms in detecting various multiphase regimes and make it challenging to precisely solve the inverse problem. The results' dependability can be increased by using advanced methods or regularization approaches. There are two categories for the algorithms in solving the inverse problem: iterative and non-iterative. Tong *et al.* [14], claim that while iterative techniques take longer to compute, they create better images than non-iterative algorithms, which are frequently faster. The measurement parameters and imaging targets determine which algorithm is best.

Besides, pipe orientation (horizontal or vertical), phase velocity, phase fraction, phase characteristics, and pipe shape are some of the factors that might affect regime patterns when recognizing multiphase regime behaviour [15]. Since different pipe orientations require for distinguished tomography concepts and methodologies, process tomography places a strong emphasis on selecting the right sensor approach. This implies that in order to guarantee precise measurements, the technique must be adjusted to the pipes' orientation. Hence, the purpose of this paper is to review process tomography techniques for identifying multiphase regimes in industrial applications. Specifically, it will discuss the two main methods (invasive and non-invasive) for visualizing and monitoring multiphase regimes, outline their benefits and drawbacks, and offer guidance for selecting appropriate process tomography techniques for further research.

Figure 3 shows the sensing techniques with different common types of process tomography that previous researchers have used. Hereafter, this review will provide new insight to researchers in making informed decisions when choosing process tomography techniques for recognizing the various kinds of multiphase flow regimes in industrial applications, including solid-liquid, liquid-liquid, and gas-liquid for their future studies.

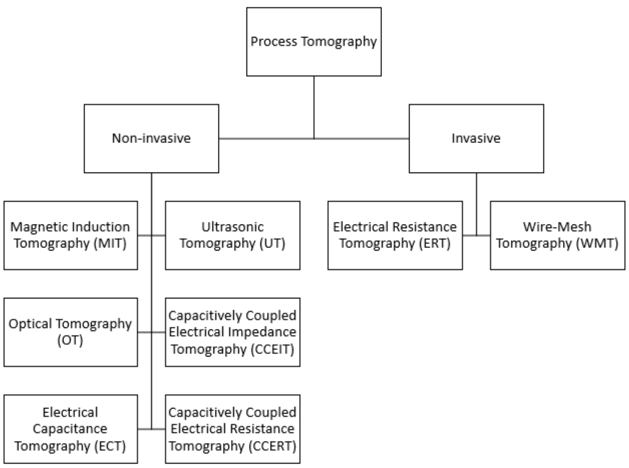


Figure 3 Sensing techniques with different common types of process tomography

3.0 NON-INVASIVE TECHNIQUES OF TOMOGRAPHY

Common types of process tomography that use a non-invasive technique studied by previous researchers are magnetic induction tomography (MIT), ultrasonic tomography (UT), optical tomography (OT), capacitively-coupled electrical impedance tomography (CCEIT), electrical capacitance tomography (ECT), and capacitively-coupled electrical resistance tomography (CCERT). The industrial application of process tomography including multiphase regimes are reviewed.

3.1 Magnetic Induction Tomography (MIT)

Using an excitation coil to create eddy currents in a conductive media, Magnetic Induction Tomography (MIT) is a non-invasive imaging modality [16]. With this kind of approach, the electrical conductivity of an object can be measured without making physical contact [17]. The MIT system uses a variety of transmitting and receiving coils to collect mutual inductance measurements. Image reconstruction software then processes the data to produce images that illustrate the distribution of electrical conductivity [18].

The goal of the non-invasive MIT sensors created by Muttakin *et al.* [19] in 2020 was to visualize liquid metal and differentiate between conductive and non-conductive pipe sections. A poly(methyl methacrylate) (PMMA) SEN pipe and liquid metal consisting of gallium, indium, and tin (GaInSn) eutectic alloys, which are liquid at room temperature, were employed in the investigation. The results showed that, despite the difficulty of capturing interior structures, there were few imaging mistakes and great accuracy in reconstructing flow patterns. Figure 4 shows the liquid metal, model for experimental measurement. Based on the study, it was found that there are negligible imaging errors and high correlations in the correct reconstruction of the flow forms, but to get the inner structures was challenging.

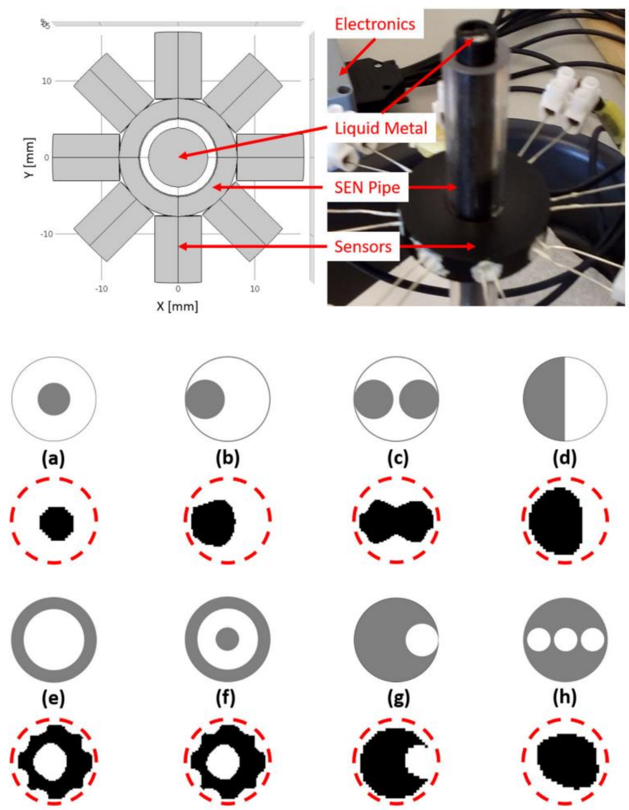


Figure 4 The liquid metal measurement model with different testing [19]

The following year, Soleimani *et al.* [20] used multi-frequency non-invasive MIT in conjunction with machine learning to study the categorization of internal voids in liquid metal. This study used machine learning approaches to categorize inclusions made of wood and liquid metal, and it describes the experimental setup with an 8-coil array, assessment measures, and neural network topologies. Multiple frequency measurements were processed to produce datasets for classification. The results of the study demonstrated that wood inclusions or voids in liquid metal could be successfully recognized by both dense fully connected neural networks (FCNN) and convolutional neural networks (CNN), yielding high precision and enabling sophisticated online control systems for liquid metal processes.

A modular MIT system for imaging low-conductivity saline solutions in non-conductive pipes was introduced by Tan *et al.* [21] in 2021, offering a technique that can be used in both industrial and health applications. In the meantime, Soleimani *et al.* [18] monitored in-situ solidification during continuous casting, a critical stage in the manufacturing of steel, using non-invasive MIT. In order to monitor the solidification process within the billet, their MIT system configuration measured the shell thickness in the cross-section of the billet (refer Figure 5). This demonstrated the system's capacity to identify conductivity fluctuations indicative of solidification.

The primary benefit of MIT is its non-contact imaging of highly conductive or metallic materials [22]. Nevertheless, the method has drawbacks, such as the lack of sophisticated tools that can provide accurate measurement and analysis, which restricts the precision and dependability of data collecting in intricate systems [18]. Capacitive coupling between transmitting and receiving coils also affects MIT and can have an impact on measurement accuracy [22].

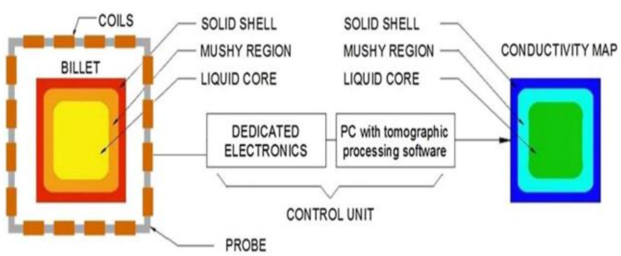


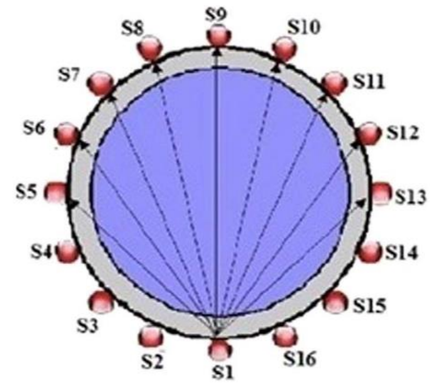
Figure 5 The MIT system scenario used in the shell-tick project to determine the shell thickness in a billet cross section [18]

3.2 Ultrasonic Tomography (UT)

Ultrasonic Tomography (UT) generates images by passing ultrasonic pulses through a material [23]. This non-invasive and non-intrusive method is appropriate for studying concentrated suspensions since it can pass through chamber and pipe walls [24]. In 2017, Goh *et al.* [24] used non-invasive UT to evaluate the sensor's capacity to detect liquid (water) and gas inside a stainless-steel pipe aiming to address the issue of delayed signal processing in transmission mode ultrasonic systems. Their research revealed a reflection problem with stainless-steel pipes, requiring exact timing in order to obtain reliable data.

In view of the wide variation in acoustic impedance, there is currently not much study on using ultrasonic tomography to image fluid flow in conductive pipelines [25]. In order to tackle this issue, Goh and colleagues [25] developed non-invasive ultrasonic measuring methods specifically for gas and liquid-containing stainless steel pipelines. Their investigation revealed that because of the concentrated beam's reduced susceptibility to wall reflections, UT systems are more appropriate for high-frequency sensors operating in the MHz range. Their study also looked into void fraction detection in a bubble column containing gas and water (see Figure 6). They found that non-invasive, high-frequency ultrasonic sensors that redistribute energy in the kHz range work well for tomographic systems that examine void fractions in stainless steel pipes.

Furthermore, a proposal of a non-invasive ultrasound system for multiphase flow imaging in non-conducting pipe was given by the authors in Ref. [2].



(a)

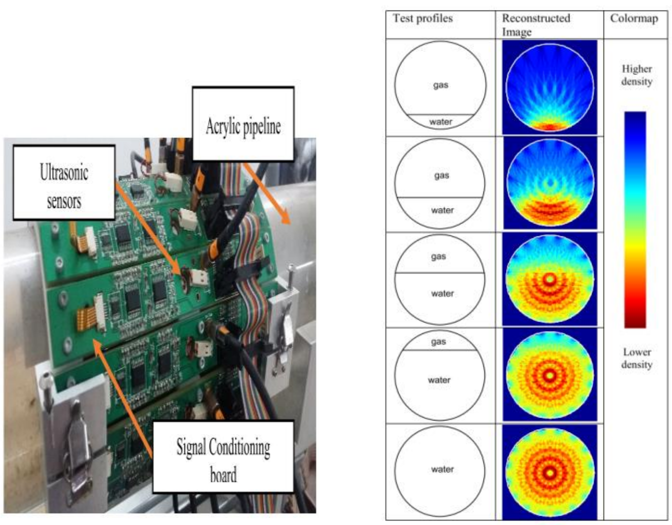
Test Object	Phantom A	Phantom B	Phantom C	Phantom D
Profile Information	Liquid Air	Liquid Air	Liquid Air	Liquid Air Air
Reconstructed Image	Phantom: 1.29 %	Phantom: 5.67 %	Phantom: 5.80 %	Phantom: 17.20 %
Theoretical Profile, %	1.03	6.47	5.60	13.10
Reconstructed Profile, %	1.29	5.67	5.80	17.20
Error, %	0.26	0.80	0.20	4.10

(b)

Figure 6 (a) UT fan beam configuration in the stainless steel pipe and (b)obtained tomograms [25]

Using continuous-wave excitation, the ultrasonic sensors were placed for contrast two-phase flow imaging. As seen in Figure 7(a), the 16-channel high-speed continuous-wave UT system was specially designed with high-voltage fan-beam transducers to meet the requirements for continuous wave excitation and fan beam angle. Although the study managed to generate a cross-sectional image, it was hampered by hazy artifacts resulting from the difficult propagation of ultrasonic waves. As can be observed in Figure 7(b), the image shows higher density measurements toward the center of the sensing zone and lower density toward the corners.

In order to quantify liquid rheology inside steel pipes, authors in Ref. [26] suggested a non-invasive in-line tomographic ultrasonic velocity meter that uses high-viscosity water for testing. Although the sensor could assess liquid rheology, the investigation found that flow inaccuracies were greatest in the center and close to the wall. Liu *et al.* [27] used sixteen channels of piezoelectric transducers affixed to the walls of a hollow plastic tube and a regularized weighted least square framework for non-invasive ultrasound imaging of oil/water two-phase flow. Continuous high-voltage excitation and measurement were made possible by this architecture. The usefulness of non-invasive ultrasound testing (UT) for assessing the quality of grouting in steel and plastic pipes was investigated by Jiangbo *et al.* [28]. Their findings illustrated the interdependencies between variables such as tendon type, pipe material, and velocity variations between concrete and grout.



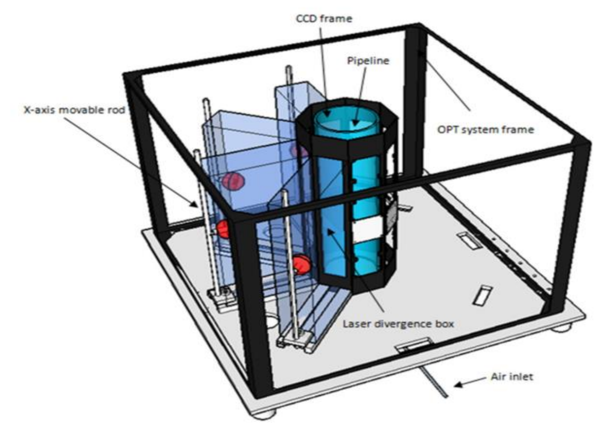
(a) (b)

Figure 7 (a) The prototype device and experimental setup; and (b) the findings of the reconstruction of the images for stratified multiphase flow [2]

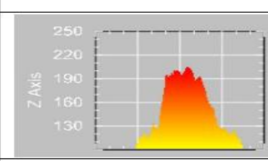
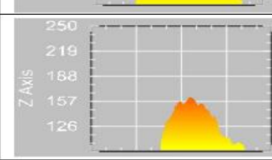
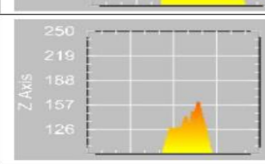
The usefulness of shielding structures in non-invasive ultrasonic transmission tomography was investigated by N. Li *et al.* [29]. Using gas and water as the medium, scientists deliberately positioned shielding bulges on the outside of an acrylic pipe wall to lessen the impact of signals generated by the pipe wall on directly received wave signals. Rapid image creation and lower energy requirements for stimulating transducers and measuring high-frequency wave propagation are two benefits of ultrasonic tomography. However, if the frequency range is not optimal, errors such as misidentified flow patterns or wrong flow rates may arise, highlighting the limitations of ultrasonic tomography and result in erroneous readings.

3.3 Optical Tomography (OT)

A hard-field sensor approach called optical tomography (OT) analyzes radiation attenuation or absorption to examine the structure and composition of materials [30]. After waves or radiation pass through the object being monitored, their intensity is assessed. Using two sensor perspectives, Jamaludin *et al.* [30] conducted studies in 2018 to detect solid and translucent objects in clear water. They used 160 and 320 sensor views to employ a charge-coupled device (CCD) and a laser diode in a non-conductive conduit. Greater image views result in greater resolution image reconstruction, according to the findings. A non-invasive and non-intrusive CCD OT system for detecting solid pollutants in crystal-clear water was created by further research by the same authors in 2020, exhibiting the system's ability to identify objects with varied opacities as shown in Figure 8.



(a)

Type of solid contamination	Side view	Z-Value
Opaque		Z > 167
Translucent		Z < 167
Transparent		Z < 167

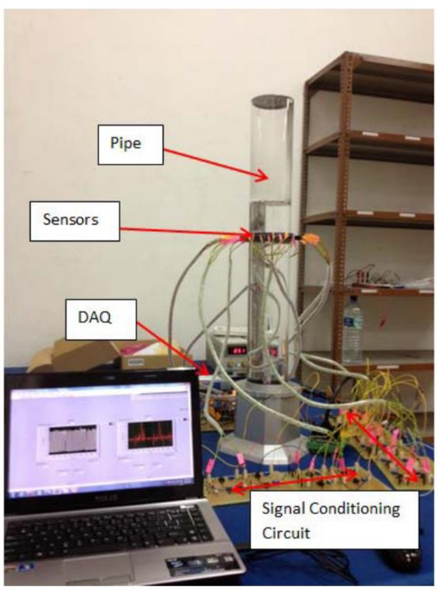
(b)

Figure 8 (a)OT hardware setup and (b) image analyses of the tomograms obtained [31]

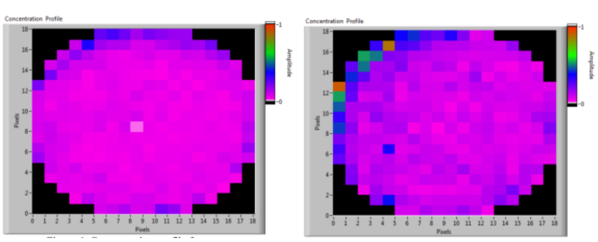
Hardware development for a non-invasive optical tracking system that can identify items inside non-conductive pipelines without penetrating the material was suggested by Muji *et al*. [32]. The design of sensors and the choice of transmitters and receivers for industrial pipeline monitoring were the main topics of this study.

In parallel, Khairi *et al*. [33] investigated an OT system that is non-invasive and may be used to check the quality of water in non-conductive pipelines. They extracted the turbidity material (M), which represents the blackness and quality of the water, using the Independent Component Analysis (ICA) method. Promising findings for enhancing water quality monitoring and treatment processes were shown by the study, as shown in Figure 9.

One of the many benefits of OT is that it's a non-invasive, non-contact approach in a safe atmosphere. Tomogram precision can be difficult to achieve, nevertheless, because to unidentified signal losses brought on by the experimental apparatus. Furthermore, dimensionality of reconstructed data, boundary effects (reflection), and complexity of initial estimations make it challenging to anticipate the optical properties of a specimen.



(a)



(b)

Figure 9 (a) The overall system designs and (b) contration profile for pure water (left side) and contaminated water (right side) [33]

3.4 Capacitively Coupled Electrical Impedance Tomography (CCEIT)

An innovative version of Electrical Resistance Tomography (ERT) called Capacitively Coupled Electrical Impedance Tomography (CCEIT) uses capacitive coupling to enable contactless measurements [34]. With the addition of total impedance measurement, this method improves on conventional resistance testing. The CCEIT principle involves applying a small, controlled electric current, typically in the milliampere range, to two electrodes placed on opposing sides of the object being photographed is the CCEIT principle, as shown in Figure 10 [35]. A voltage differential is created between the electrodes as a result of the current passing through the object. Through the measurement of capacitance between these electrodes, CCEIT is able to generate an image that illustrates the interior structure of the object.

Yuxin Wang *et al*. [36] presented a technique in 2019 for employing CCEIT to reconstruct images of gas-liquid two-phase flow based on the total impedance of the flow. By combining the K-means clustering technique for automatic grey level thresholding and the Local Binary Pattern (LBP) algorithm for initial image reconstruction, they created a revolutionary image reconstruction algorithm.

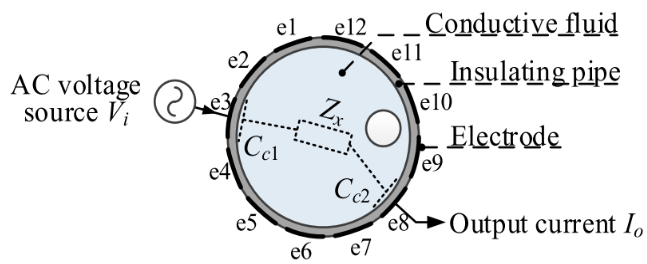


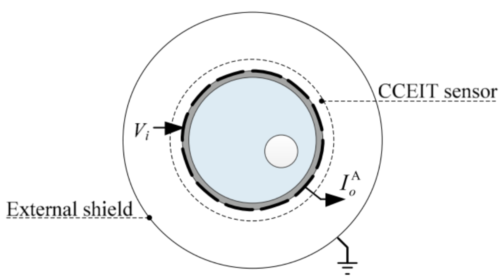
Figure 10 Measurement principle of CCEIT [35]

The approach's feasibility and efficiency were proven by the experimental findings, which produced an acceptable level of image reconstruction quality.

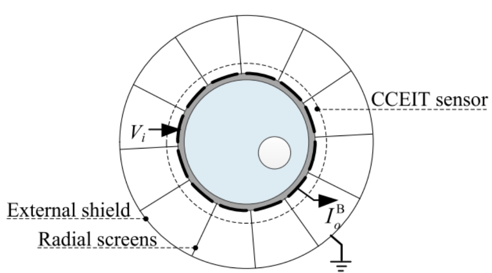
In 2021, Xuekai He *et al*. [34] presented a novel method for CCEIT image reconstruction that used the Linear Back Projection (LBP) algorithm, the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm, and image fusion approaches. Using LBP, original images of real and imaginary components were obtained, and then the grey level thresholding of DBSCAN was applied to refine the images. Experiments with a 12-electrode prototype CCEIT system proved the efficacy of this method and produced final images with acceptable quality.

Three variants of CCEIT sensors were examined by Yandan Jiang *et al*. [35]: unshielded, shielded configuration A (external shield), and shielded configuration B (radial screens with an external shield). A and B, the insulated arrangements, are shown in Figure 11. According to the simulation results, which are displayed in Figure 12, shielded setups raised the sensitivity distributions' overall average sensitivity, with configuration A usually improving uniformity and configuration B generally decreasing it.

In short, CCEIT has several of benefits, including as its non-invasive and contactless measurement capabilities, its applicability for applications where direct contact with the medium is not desirable or feasible, and its capacity to measure both resistance and capacitance for more comprehensive information. Nonetheless, the method is not without its drawbacks, including the complexity of image reconstruction algorithms, the possibility of decreased sensitivity in some configurations when compared to conventional ERT, and the issue of attaining a consistent sensitivity distribution over the measurement region. Despite these drawbacks, research is still being done to enhance CCEIT's functionality and suitability for use in a range of scientific and industrial settings.



(a)



(b)

Figure 11 (a) Shielded configuration A,(b) Shielded configuration B [35]

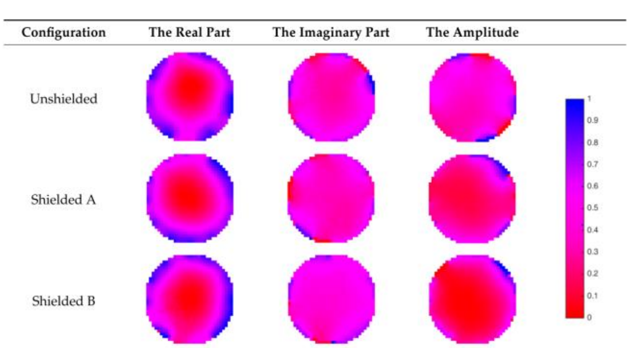


Figure 12 Imaging results obtained by the CCEIT prototypes [35]

3.5 Electrical Capacitance Tomography (ECT)

The basis of Electrical Capacitance Tomography (ECT) is the use of an ECT sensor to measure the permittivity distribution inside an object [37]. A multiphase experiment and sensor modeling technique for non-invasive, capacitance-based flow regime detection were presented by authors in Ref. [37] in 2017. In a Plexiglas pipe, the electrical properties of mineral oil, water, and air were observed in this investigation. With potential applicability to different sensing methods, their "frame-by-frame" time series analysis proved useful in yielding meaningful insights utilizing non-intrusive sensing techniques. The goal of Tian *et al.*'s [38] fuzzy PID-controlled iterative Calderon approach for non-invasive ECT was to use solid and air mediums to rebuild binary distributions in a circular electrode ECT sensor. As shown in Figure 13, the outcomes showed that the approach could produce images with sharp edges and well-defined binary distribution shapes.

In an additional work, Omar *et al.* [39] used non-invasive ECT to look into the large-diameter vertical Perspex conduit's fluid-structure behavior in gas-oil two-phase flow. The evolution of flow configurations in the vertical segment downstream from the mixer was studied in depth. Furthermore, an integrated non-invasive electrostatic sensor (ES) and electrostatic current tracking (ECT) system was developed by Long *et al.* [40] to track volume flow rates in particle processes in non-conducting pipes. According to their findings, the sensor could monitor volume flow rate, velocity, and particle concentration in particulate processes with an effective low relative error.

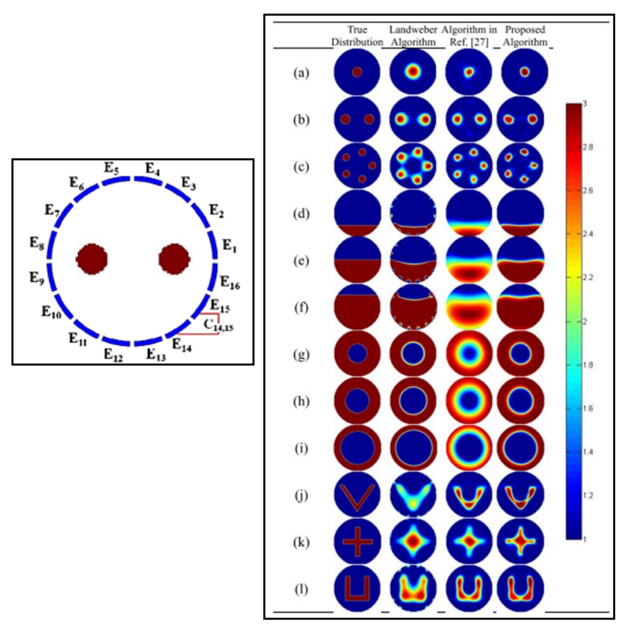


Figure 13 Tomographic sensor with 16 electrodes (left side) and Reconstructed images of different algorithms (right side) of ECT system [38]

A water fraction measurement technique for gas-water two-phase flow was presented by Liu *et al.* [41] in 2020. It made use of an acrylic pipe and a heuristic approach based on non-invasive ECT image post-processing technology. This approach showed good practical water fraction calculating skills and minimal relative error. In order to achieve high-quality imaging, Li *et al.* [42] introduced an image reconstruction strategy for non-invasive ECT that uses a parametric level set (PLS) approach. The technique produced high-quality images of water leaks by updating reconstruction forms in response to modifications to the level set function, as illustrated in Figure 14. Using a digital signal processing (DSP) control system in a ceramic pipe, Gao *et al.* [43] developed a non-invasive ECT system to handle the challenge of recognizing gas/solid two-phase flow in pneumatic conveying of pulverized coal. Their technology, which could theoretically capture 200 frames per second, showed excellent stability and sensitivity.

In conclusion, ECT's non-invasive, non-intrusive, and non-radiative characteristics make it an appealing technique for imaging a variety of applications, especially in dielectric media. There is a study gap concerning conducting pipe applications using invasive ECT techniques, as the majority of multiphase flow investigations have concentrated on non-conducting pipe materials.

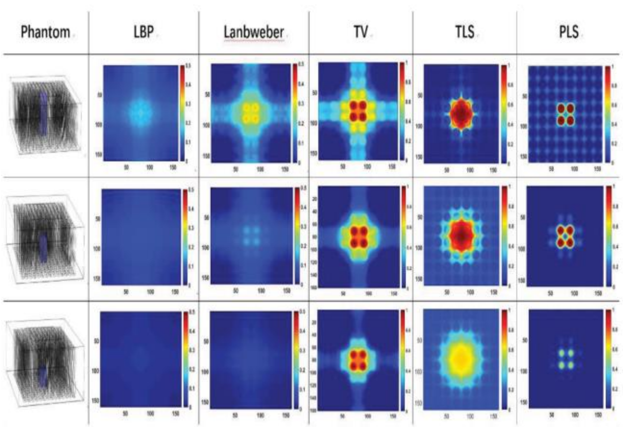


Figure 14 Imaging reconstructions from simulated data using PLS and other algorithms [42]

3.6 Capacitively Coupled Electrical Resistance Tomography (CCERT)

An improved version of Electrical Resistance Tomography (ERT) that allows imaging of conductive materials without direct contact is called Capacitively Coupled Electrical Resistance Tomography (CCERT). CCERT is best suited for static or slowly moving systems since it concentrates on electrical resistivity, while CCEIT monitors electrical impedance and is best suited for dynamic processes (as reviewed in sub topic 3.4).

A CCERT system with shielding for gas-liquid two-phase flow (see Figure 15) was recently introduced by Xintong Fang *et al.* [44]. This system consists of hardware, experimental components, and an image reconstruction algorithm based on a combination of truncated singular value decomposition (TSVD) and density peak clustering (DPC). This methodology has demonstrated higher imaging quality when compared to older methods.

Besides, a 12-electrode sensor was used by Chunfen Luo *et al.* [45] to create a unique deep imaging technique for multifrequency CCERT (MFCCERT) that detects multifrequency impedance. As seen in Figure 16, the outcomes proved the efficacy of this deep imaging approach by showcasing superior information fusion and picture reconstruction skills.

For CCERT, Zheng Wang *et al.* [46] suggested an image reconstruction technique that combines K-means and DPC. Target zones are identified using an enhanced DPC after linear back projection (LBP) is used to create the original image. Grey level thresholds are determined by an updated K-means algorithm, which leads to better image quality with less operator interaction. Moreover, A tactile sensor system based on CCERT was presented by Dingmin Xu *et al.* [47] to solve concerns about stress concentration from bulky wiring and durability. By improving the input and output impedance of the system, a bidirectional buffer lowers complexity. The force distribution, amplitude, and position are all precisely measured by this sensor system. Besides, a specialized image reconstruction method using a 2-electrode excitation approach for a 12-electrode CCERT system was presented by Zhen Xu *et al.* [48]. To enhance image quality, the technique makes use of TSVD and the algebraic reconstruction technique (ART).

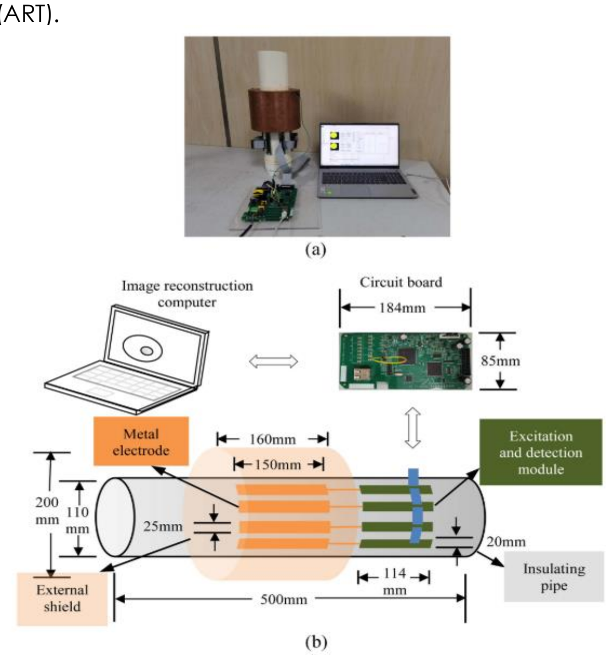


Figure 15 Developed a shielded CCERT system. (a) Hardware system. (b) Diagram of the structure [44]

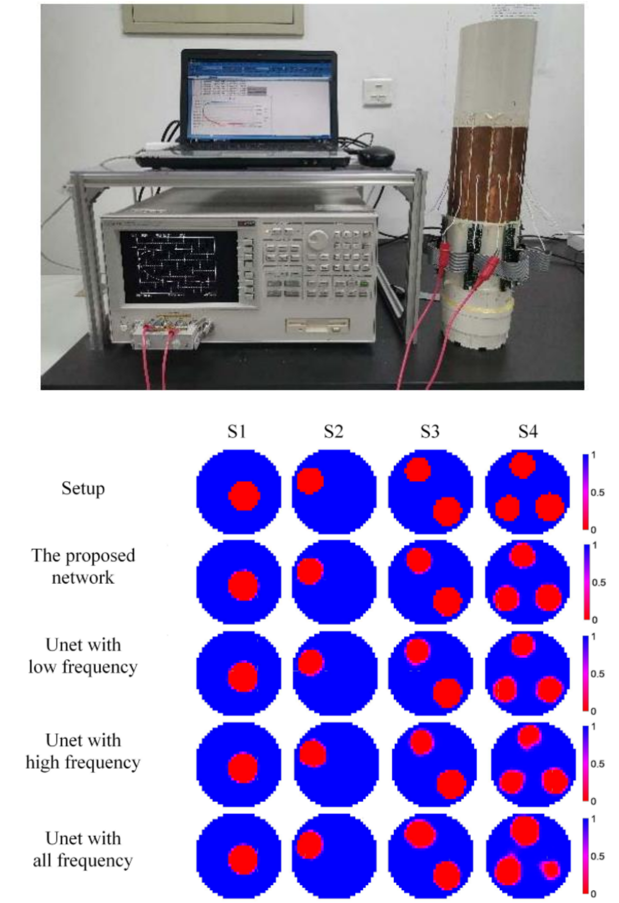


Figure 16 Experimental setup (top) and reconstructed images using simulation data from several techniques (bottom) [45]

The benefit of CCERT measurement is that it does not require physical sensors to make contact with the item or medium. However, due to the electrode layout and quantity, it may not be able to catch small details and localized fluctuations in the item or system being scanned, which limits its spatial resolution.

4.0 INVASIVE TECHNIQUES OF TOMOGRAPHY

Common types of process tomography that use an invasive technique studied by previous researchers are electrical resistance tomography (ERT) and wire mesh tomography (WMT). In this section, the industrial applications of process tomography, including multiphase regimes, are reviewed.

4.1 Electrical Resistance Tomography (ERT)

By examining how electrical conductivity is distributed across an area of interest, a method called Electrical Resistance Tomography (ERT) can produce images [10]. It measures electrical resistivity, or the resistance to the flow of electric current, and is especially useful in conductive media like seawater or salty water. By resolving the inverse problem, ERT concentrates on the resistive part of impedance and visualizes an object's electrical resistivity through repeated resistance measurements.

Liu Yang *et al.* [49] presented a technique that uses invasive ERT in conjunction with the Kalman estimate approach in a closed non-conducting pipeline to measure the solid component fraction in multiphase flows, such as soil solids and saltwater. This method was verified in a practical dredge engineering application; nevertheless, the estimation accuracy was impacted by several errors in the Kalman filter parameters.

A modified invasive ERT system for wastewater monitoring was investigated by Wu *et al.* [50]. This system used a limited region image reconstruction technique based on Jacobian reformulation in a non-conducting conduit. This technique improved robustness in the conductive zone and successfully imaged inclusions (see Figure 17). In 2021, Zhang *et al.* [51] investigated liquid-solid two-phase flow in a horizontal non-conducting pipeline using invasive ERT in conjunction with pulse wave ultrasonic Doppler (PWUD). Phase fractions and flow velocity were among the flow characteristics that this combination successfully recorded.

Similar to this, authors in Ref. [52] and [53] used invasive ERT to monitor multiphase flow in non-conductive pipes, concentrating on whirling flow fields and settling slurry pipe flow, respectively. Laplace and GREIT fared well in visual inspection and performance measures, according to a study in [52] that compared algorithms (see Figure 18). Furthermore, the study illustrated how guide vanes can be used to separate oil-water mixtures efficiently, offering important information for the design of vane-type pipe separators.

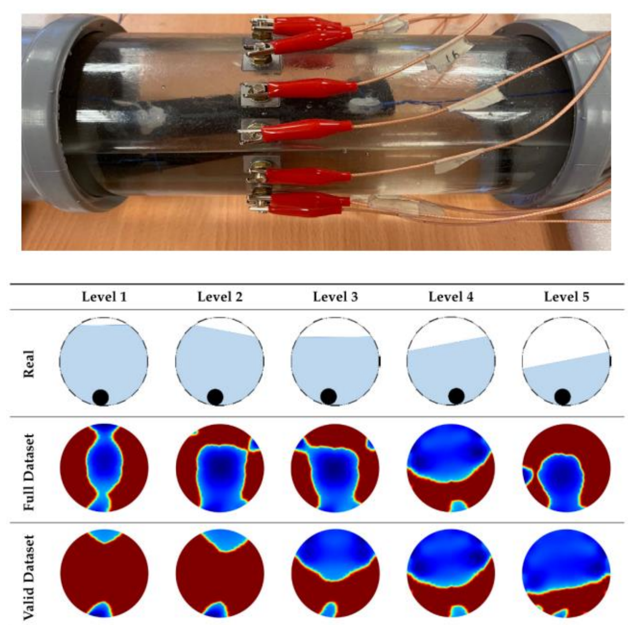


Figure 17 Phantom tested and small inclusion tests comparison [50]

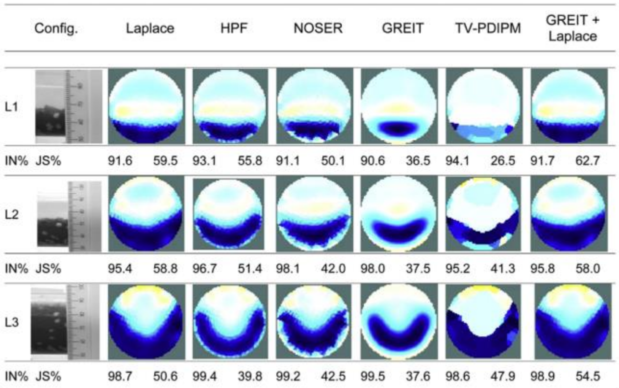


Figure 18 Comparing image reconstructions for measurements of bed configuration, L1–L3 [52]

Moreover, a technique to improve ERT measurements on slurry pipe flow was presented by Hashemi *et al.* [54] in 2021. It took into account the concentrations of sand, water, or surface-active clays in a non-conducting recirculating pipe. The results of the investigation demonstrated that the application of a correction model greatly increased the measurement accuracy for clay-containing slurries.

Given its quick and easy data processing, ERT is preferred in multiphase flow applications. However, its use is restricted to electrically conductive media, and its disadvantages include low spatial resolution, noise sensitivity, and electrode placement sensitivity. Results and the reconstructed electrical conductivity might be greatly impacted by electrode displacements.

4.2 Wire Mesh Tomography (WMT)

An imaging method called wire mesh tomography (WMT) uses a wire mesh sensor to assess differences in conductivity within an item or medium [55]. During the sensor's placement around the target, a current of electricity is used. Computational algorithms are employed to measure and process the voltages obtained, consequently creating an image of the internal conductivity distribution. WMT is an affordable, non-invasive technique that has uses in both medical imaging and industrial process monitoring.

An invasive wire-mesh sensor with a differential measuring mode was created by Zhai *et al.* [56] to observe small bubbles. Through studies that simulated gas-water fluxes in a non-conducting tube, their study verified the WMT system. The visualizations revealed improved precision in measuring gas holdup in bubbly flows and showed significant agreement with high-speed camera pictures (see Figure 19). Furthermore, utilizing sparse minimization, Ren *et al.* [57] developed invasive wire-mesh imaging for water-air flow in a non-conducting pipe. With fewer artifacts, sharper phase interfaces, and improved spatial resolution from the wire-mesh sensor, this technique prepared the way for theorized observations of exact flow properties.

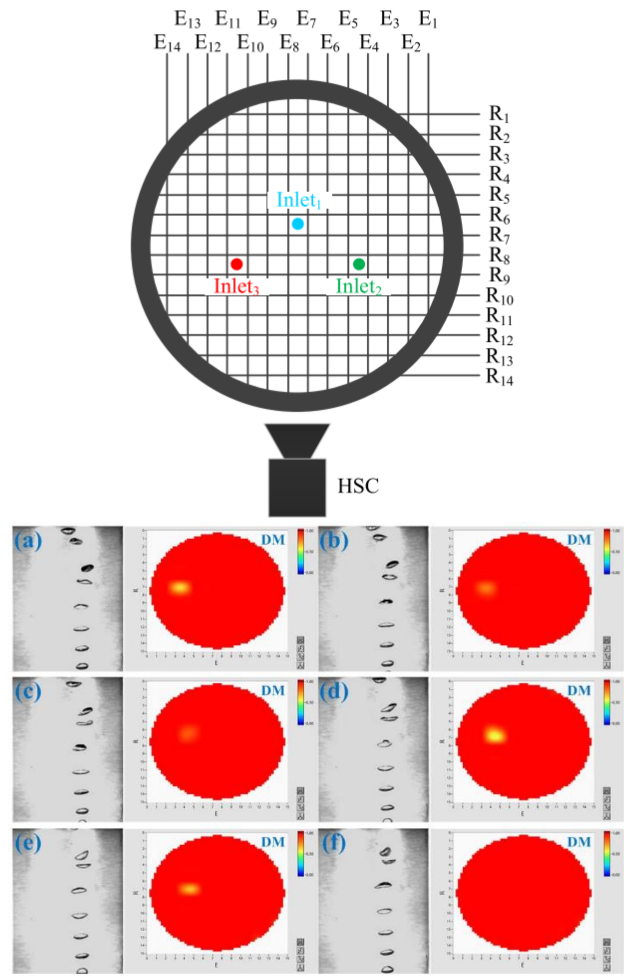


Figure 19 Positioning of sensor (top) and single bubble captured by high-speed camera using wms in differential mode (bottom) [56]

Furthermore, Ofuchi *et al.* [58] used invasive WMT in oil and gas applications to evaluate two-phase flow in a cyclonic flow distribution system. Wire-mesh sensors monitored void fractions at multiple locations, such as the input, inside the non-conducting cyclonic chamber, and at the four outputs, in addition to detecting patterns of water and air flow. But the study also found difficulties with spatial resolution, with fluctuations ranging from 1 to 4 percent for bubbly flows and up to a 20 percent peak at low void fractions due to sensor pitch effects. In addition, a high-degree total variation (HDTV) image method based on the total variation (TV) technique was used by Sun *et al.* [59] to solve uneven reconstructed images in multiphase flow that resulted from the rectangular measurements of the sensor. The objective was to use invasive WMT to get a tomogram of the oil and gas medium in a non-conducting conduit. The study discovered that tomogram accuracy in WMT might be increased by modifying parameters within a particular range.

For evaluating conductivity fluctuations in multiphase flows, Wire Mesh Tomography (WMT) is a cost-effective and invasive imaging approach. It might not work well in conducting pipes, though, and is only suitable for non-conducting pipe applications. In addition, because the sensor structure is rectangular in shape, the images it generates may appear jagged.

6.0 ENHANCING DIELECTRIC MONITORING IN CONDUCTIVE PIPES USING INVASIVE ECT TECHNIQUES

Normal Electrical Capacitance Tomography (ECT) works well with non-conductive materials such as slurry or oil. Nevertheless, there are difficulties when using it in conductive pipes, such steel ones. In these situations, non-invasive ECT—which uses sensors outside the pipe—is useless since the conductive pipe obstructs the transmission and receipt of signals. Consequently, the projection signal stays inside the pipe's perimeter and is unable to enter the detecting channels. While industries frequently use conductive materials like stainless steel and carbon steel [60], the majority of current ECT research focuses on non-conductive pipes like acrylic or glass [61,62].

Future studies should investigate invasive ECT methods to efficiently monitor dielectric regimes within conductive pipelines in order to close this gap. Compared to systems with more electrodes, our proposed initial study would use an invasive ECT device with 12 electrodes, which balances cost and functionality. By carefully positioning these electrodes inside the pipe wall (refer to Figure 20 and Figure 21, the excitation channel will be able to send voltage signals through the medium. To guarantee precise signal capture, the detection channels which are set to float will be connected to circuits for signal conditioning. In order to make the analysis of multiphase regimes easier, this configuration attempts to generate distinct tomograms of the region of interest.

With an additional insulator layer to avoid short-circuiting between the metal electrodes and the pipe, the suggested sensor design is similar to the conducting boundary approach utilized in Electrical Resistance Tomography (ERT) [63]. This design makes sure the signal travels around the pipe's perimeter efficiently. Whereas ERT concentrates on electrical conductivity, ECT is more adaptable to different media since it focuses on the distribution of dielectric permittivity. Motivated by earlier work [64], the addition of a driven guard improves signal focus and precision, which is important for industrial applications in oil and gas.

The viability of applying invasive ECT in steel pipes has been shown by simulation results using COMSOL Multiphysics [65]. This suggests that the quality of tomograms obtained from this approach could be on equivalence with those obtained from non-invasive ECT in non-conductive pipes. By developing this method, we can meet industry demands by greatly enhancing our capacity to monitor dielectric regimes in conductive environments.

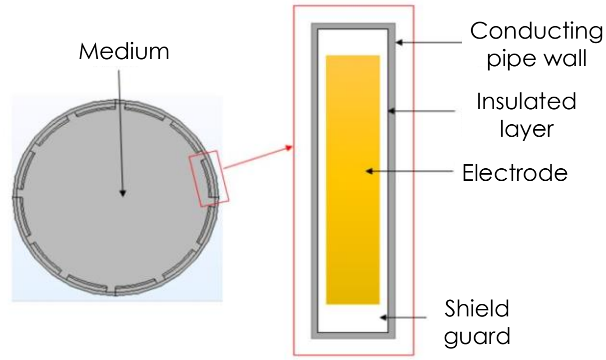


Figure 20 12-electrodes inside conducting pipe wall (left-side) and front view of the ECT sensor (right-side)

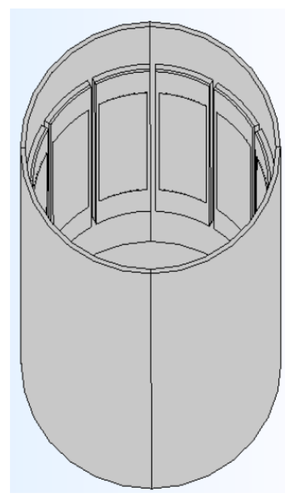


Figure 21 3D geometry for 12-electrodes of ECT system

7.0 CONCLUSION

The strengths and drawbacks of invasive and non-invasive process tomography approaches have been reviewed in this article. When used in non-conductive surroundings, non-invasive techniques such as ECT and MIT provide quick imaging with little disturbance; nevertheless, they are less effective in conductive environments. Although they can be more intrusive, invasive techniques like ERT and WMT offer improved accuracy and resolution in conductive medium, making them appropriate for comprehensive imaging of multiphase flows. These issues are addressed by the suggested invasive ECT method for dielectric monitoring in conductive pipes, especially steel, which incorporates electrodes inside the pipe and uses a driven guard to improve accuracy. This approach is in line with industry requirements, particularly in industries like oil and gas where accurate monitoring is crucial. The decision between these methods should ultimately depend on the particular application requirements, and more study will be required to improve and broaden their scope.

Acknowledgement

The authors would like to thank the Ministry of Higher Education for providing financial support under Fundamental research grant No. FRGS/1/2021/TK0/UMP/02/11 (University reference RDU210111) and Universiti Malaysia Pahang Al-Sultan Abdullah for fee funding and laboratory facilities.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

References

[1] J. Yao, M. Takei. 2017. Application of Process Tomography to Multiphase Flow Measurement in Industrial and Biomedical Fields: A Review. *IEEE Sensors Journal*. 17: 8196–8205. https://doi.org/10.1109/JSEN.2017.2682929.

[2] N. A. Zulkiflli, S. Ibrahim, M. H. F. Rahiman, J. Pusppanathan, R. A. Rahim, K. S. Tee, F. A. Phang, N. D. Nawi, N. M. N. Ayob. 2019. Ultrasound Tomography Hardware System for Multiphase Flow Imaging. *Proceedings of the 2019 IEEE International Conference on Signal and Image Processing Applications, ICSIPA 2019*. 264–268. https://doi.org/10.1109/ICSIPA45851.2019.8977725.

[3] N. F. Mukaiyin, E. J. Mohamad, R. Abdul Rahim, J. Pusppanathan, N. N. Nasir, Z. Zakaria, I. M. Zainal Abidin, O. Mohd Faizan Mawrah, N. A. Zulkifli. 2019. Investigation of Capabilities of Electromagnetic Tomography for Pipeline Imaging. *Jurnal Teknologi*. 81: 149–154. https://doi.org/10.11113/jt.v81.13197.

[4] G. Steiner, F. Podd. 2006:. A Non-invasive and Non-intrusive Ultrasonic Transducer Array for Process Tomography. *Proceedings of the XVIIII IMEKO World Congress Metrology for a Sustainable Development*, Brazil. 17–22.

[5] A. Bouzid, S. Chidami, T.Q. Lailler, A.C. García, T. Ould-bachir, J. Chaouki. 2024. Innovative Non-invasive and Non-intrusive Precision Thermometry in Stainless-steel Tanks using Ultrasound Transducers. *Sensors*. 24: 3404. https://doi.org/10.3390/s24113404.

[6] T. Rymarczyk. 2018. A Nondestructive Distributed Sensor System for Imaging in Industrial Tomography. Pengzhong Li (Ed.). New Trends in Industrial Automation. IntechOpen. https://doi.org/10.5772/intechopen.79567.

[7] H. Wu, B. Buschle, Y. Yang, C. Tan, F. Dong, J. Jia, M. Lucquiaud. 2018. Liquid Distribution and Hold-up Measurement in Counter Current Flow Packed Column by Electrical Capacitance Tomography, *Chemical Engineering Journal*. 353: 519–532. https://doi.org/10.1016/j.cej.2018.07.016.

[8] W. Zhang, C. Tan, F. Dong. 2020. Dual-Modality Tomography by ERT and UTT Projection Sorting Algorithm. *IEEE Sensors Journal*. 20: 5415–5423. https://doi.org/10.1109/JSEN.2020.2969529.

[9] Y. Abdul Wahab, R. Abdul Rahim, M. H. Fazalul Rahiman, S. Ridzuan Aw, F. R. Mohd Yunus, C. L. Goh, H. Abdul Rahim, L. P. Ling. 2015. Non-invasive Process Tomography in Chemical Mixtures – A Review. *Sensors and Actuators B: Chemical*. 210: 602–617. https://doi.org/10.1016/j.snb.2014.12.103.

[10] Y. Wang, Y. Yang. 2017. Refined Composite Multivariate Multiscale Fuzzy Entropy Analysis of Horizontal Oil-water Two-phase Flow. *ICCSE 2017 - 12th International Conference on Computer Science and Education*. 423–428. https://doi.org/10.1109/ICCSE.2017.8085529.

[11] C. Li, H. Wang, M. Wang, S. Ma, T. Gao, F. Wang, S. Chen. 2020. Optimization of Geometrical Parameters of ECT Sensor for Power Cable Insulation Detection. *7th IEEE International Conference on High Voltage Engineering and Application, ICHVE 2020 - Proceedings*. 2–5. https://doi.org/10.1109/ICHVE49031.2020.9279522.

[12] U. Hampel, L. Babout, R. Banasiak, E. Schleicher, M. Soleimani, T. Wondrak, M. Vauhkonen, T. Lähivaara, C. Tan, B. Hoyle, A. Penn. 2022. A Review on Fast Tomographic Techniques and Their Potential Application in Industrial Process Control. *Sensors*. 22. https://doi.org/10.3390/s22062309.

[13] Y. Abdul Wahab. 2017. 2 MHz Electrical Resistance Tomography for Static Liquid-Solid Profile Measurement. Universiti Teknologi Malaysia.

[14] G. Tong, S. Liu, S. Liu. 2019. Computationally Efficient Image Reconstruction Algorithm for Electrical Capacitance Tomography. *Transactions of the Institute of Measurement and Control*. 41: 631–646. https://doi.org/10.1177/0142331218763013.

[15] R. Yan, H. Viumdal, S. Mylvaganam. 2020. Process Tomography for Model Free Adaptive Control (MFAC) Via Flow Regime Identification in Multiphase Flows. *IFAC-PapersOnLine*. 53: 11753–11760. https://doi.org/10.1016/j.ifacol.2020.12.681.

[16] J. Wang, X. Wang, D. Yang, K. Wang, Y. Zhou. 2018. Magnetic Induction Tomograp Soft. *IOP Conference Series: Materials Science and Engineering*. 042001. https://doi.org/10.1088/1757-899X/394/4/042001.

[17] M. Soleimani, W. R. B. Lionheart, A. J. Peyton. 2007. Image Reconstruction for High-contrast Conductivity Imaging in Mutual Induction Tomography for Industrial Applications. *IEEE Transactions on Instrumentation and Measurement*. 56: 2024–2032. https://doi.org/10.1109/TIM.2007.895598.

[18] M. Soleimani, F. Li, S. Spagnul, J. Palacios, J. I. Barbero, T. Gutiérrez, A. Viotto. 2020. In Situ Steel Solidification Imaging in Continuous Casting using Magnetic Induction Tomography. *Measurement Science and Technology*. 31: 065401. https://doi.org/10.1088/1361-6501/ab6f30.

[19] I. Muttakin, T. Wondrak, M. Soleimani. 2020. Magnetic Induction Tomography Sensors for Quantitative Visualization of Liquid Metal Flow Shape. *IEEE Sensors Letters*. 4: 5–8. https://doi.org/10.1109/LSENS.2020.3000292.

[20] I. Muttakin, M. Soleimani. 2021. Interior Void Classification in Liquid Metal using Multi-frequency Magnetic Induction Tomography with a Machine Learning Approach. *IEEE Sensors Journal*. 21: 23289–23296. https://doi.org/10.1109/JSEN.2021.3109629.

[21] C. Tan, Y. Chen, Y. Wu, Z. Xiao, F. Dong. 2021. A Modular Magnetic Induction Tomography System for Low-conductivity Medium Imaging. *IEEE Transactions on Instrumentation and Measurement*. 70. https://doi.org/10.1109/TIM.2021.3073439.

[22] M. S. Badri Mansor, Z. Zakaria, R. Abdul Rahim, M. F. Abdul Sahib, Y. Md Yunos, S. Sahlan, S. Bunyamin, K. H. Abas, M. H. Izran Ishak, K. Danapalasingam. 2015. Magnetic Induction Tomography: A Brief Review. *Jurnal Teknologi*. 73: 91–95.

[23] O. Qorbani, E. N. Aghdam. 2020. Two-phase Flow Measuring with Ultrasonic Tomography. *Archives of Acoustics*. 45: 459–465. https://doi.org/10.24425/aoa.2020.134062.

[24] C. L. Goh, A. R. Ruzairi, F. R. Hafiz, Z. C. Tee. 2017. Investigation into Slow Scan Front-end Control of a Transmission Mode Ultrasonic System. *IEEE Sensors Journal*. 17: 5136–5142. https://doi.org/10.1109/JSEN.2017.2717506.

[25] C. L. Goh, R. A. Rahim, H. F. Rahiman, T. Zhen Cong, Y. A.

Wahad. 2017. Simulation and Experimental Study of the Sensor Emitting Frequency for Ultrasonic Tomography System in a Conducting Pipe. *Flow Measurement and Instrumentation*. 54: 158–171. https://doi.org/10.1016/j.flowmeasinst.2017.01.003.

[26] V. N. P. L. M. J., S. U., G. L. F. G., P. D., C. F., G. M., E. J. M. Giling. 2018. Development of a Non-intrusive In-line Tomographic Ultrasonic Velocity Meter to Measure Liquid Rheology. *2018 IEEE International Ultrasonics Symposium (IUS)*. 1–4. https://doi.org/10.1109/ULTSYM.2018.8580166.

[27] H. Liu, C. Tan, F. Dong. 2020. Continuous-wave Ultrasonic Tomography for Oil/water Two-phase Flow Imaging using Regularized Weighted Least Square Frameworke. *Transactions of the Institute of Measurement and Control*. 42: 666–679. https://doi.org/10.1177/0142331219853073.

[28] L. Jiangbo, S. Tang, X. Dai, Z. Fang. 2018. Investigation into the Effectiveness of Ultrasonic Tomography for Grouting Quality Evaluation. *KSCE Journal of Civil Engineering*. 22: 5094–5101. https://doi.org/10.1007/s12205-018-0091-x.

[29] N. Li, K. Xu, S. Li. 2018. Numerical Simulation Study on Effectiveness of Shielding Structure on Ultrasonic Transmission Tomography. *Eurasip Journal on Wireless Communications and Networking*. 2018: 1–8. https://doi.org/10.1186/s13638-018-1094-5.

[30] J. Jamaludin, R. A. Rahim, M. H. Fazul Rahiman, J. Mohd Rohani. 2018. Analysis on the Effect of Sensor Views in Image Reconstruction Produced by Optical Tomography System using Charge-coupled Device. *IEEE Transactions on Image Processing*. 27: 1689–1696. https://doi.org/10.1109/TIP.2017.2783620.

[31] J. Jamaludin, R. Abdul Rahim, M. H. F. Rahiman, J. M. Rohani. 2020. CCD Optical Tomography System to Detect Solid Contamination in Crystal-clear Water. *IEEE Transactions on Industrial Electronics*. 67: 3248–3256. https://doi.org/10.1109/TIE.2019.2908589.

[32] S. Z. M. Muji, R. J. Karim, R. Abdul Rahim. 2013. The Development of Hardware for Optical Tomography System. *4th International Conference on Photonics. ICP 2013 - Conference Proceeding, IEEE*. 259–261. https://doi.org/10.1109/ICP.2013.6687132.

[33] M. T. M. Khairi, S. Ibrahim, M. A. Md Yunus, M. N. M. Sulaiman. 2013. An Application of Independent Component Analysis Method for Estimating the Quality Level of Water using Optical Tomography. *Proceedings - 2013 IEEE 4th Control and System Graduate Research Colloquium, ICSGRC 2013, IEEE*. 11–16. https://doi.org/10.1109/ICSGRC.2013.6653267.

[34] X. He, Y. Jiang, B. Wang, H. Ji, Z. Huang. 2021. An Image Reconstruction Method of Capacitively Coupled Electrical Impedance Tomography (CCEIT) based on DBSCAN and Image Fusion. *IEEE Transactions on Instrumentation and Measurement*. 70: 1–11. https://doi.org/10.1109/TIM.2021.3056739.

[35] Y. Jiang, X. He, B. Wang, Z. Huang, M. Soleimani. 2020. On the Performance of a Capacitively Coupled Electrical Impedance Tomography Sensor with Different Configurations. *Sensors (Switzerland*). 20: 1–18. https://doi.org/10.3390/s20205787.

[36] Y. Wang, H. Ji, Z. Huang, B. Wang, H. Li. 2020. Study on Image Reconstruction of Capacitively Coupled Electrical Impedance Tomography (CCEIT). *9th World Congress on Industrial Process Tomography* (WCIPT9). 094002. https://doi.org/10.1088/1361-6501/ab1324.

[37] W. Tian, J. Sun, M. F. Ramli, J. Wang, W. Yang. 2017. An Electrical Capacitance Tomography Sensor With Variable Diameter. *IEEE Sensors Journal*. 17: 2089–2099. https://doi.org/10.1109/JSEN.2017.2667716.

[38] Y. Tian, Z. Cao, D. Hu, X. Gao, L. Xu, W. Yang. 2021. A Fuzzy PID-controlled Iterative Calderon's Method for Binary Distribution in Electrical Capacitance Tomography. *IEEE Transactions on Instrumentation and Measurement*. 70. https://doi.org/10.1109/TIM.2021.3052249.

[39] R. Omar, B. Hewakandamby, A. Azzi, B. Azzopardi. 2018. Fluid Structure Behaviour in Gas-oil Two-phase Flow in a Moderately Large Diameter Vertical Pipe. *Chemical Engineering Science*. 187: 377–390. https://doi.org/10.1016/j.ces.2018.04.075.

[40] J. Long, M. A. R. Frias, K. Z. Mokhtar, W. Yang. 2018. An Integrated ECT and Electrostatic Sensor for Particulate Flow Measurement. *IST 2018 - IEEE International Conference on Imaging Systems and Techniques, Proceedings*. 1–5. https://doi.org/10.1109/IST.2018.8577202.

[41] B. Liu, C. Tang, K. Tang, H. Hu. 2020. A Water Fraction Measurement Method using Heuristic-Algorithm-based Electrical Capacitance Tomography Images Post-processing Technology. *IEEE Access*. 8: 206418–206426. https://doi.org/10.1109/ACCESS.2020.3037721.

[42] R. Li, Y. Zhang, L. Peng, X. Liao. 2020. An Image Reconstruction for Electrical Capacitance Tomography using Parametric Level Set. *2020 5th International Conference on Computer and Communication Systems,* ICCCS. 2020384–390. https://doi.org/10.1109/ICCCS49078.2020.9118589.

[43] Y. Gao, S. Chen, Q. Xu. 2018. Application of Electrical Capacitance Tomography in Pneumatic Conveying of Pulverized Coal. *2018 International Conference on Information, Cybernetics, and Computational Social Systems,* ICCSS 2018, IEEE. 359–363. https://doi.org/10.1109/ICCSS.2018.8572356.

[44] X. Fang, Y. Jiang, H. Ji, B. Wang, Z. Huang. 2024. A New CCERT System with Shielding for Gas-liquid Two-phase Flow. *IEEE Transactions on Industrial Electronics*. 71: 4241–4251. https://doi.org/10.1109/TIE.2023.3273267.

[45] C. Luo, L. Zhu, Y. Jiang, M. Zhang, H. Ji, B. Wang, Z. Huang. 2023. A Two-stream Deep Imaging Method for Multifrequency Capacitively Coupled Electrical Resistance Tomography. *IEEE Sensors Journal*. 23: 4362–4372. https://doi.org/10.1109/JSEN.2022.3200960.

[46] Z. Wang, Y. Jiang, J. Huang, B. Wang, H. Ji, Z. Huang. 2023. A New Image Reconstruction Algorithm for CCERT based on Improved DPC and K-Means. *IEEE Sensors Journal*. 23: 4476–4485. https://doi.org/10.1109/JSEN.2022.3185736.

[47] D. Xu, X. Li, S. Zhang. 2022. A CCERT-based Tactile Sensor with Bidirectional Buffer. *IEEE Sensors Journal*. 22: 19480–19489. https://doi.org/10.1109/JSEN.2022.3205034.

[48] Z. Xu, J. Huang, Y. Jiang, B. Wang, Z. Huang, M. Soleimani. 2021. An Image Reconstruction Algorithm for a 12-electrode Capacitively Coupled Electrical Resistance Tomography System under 2-electrode Excitation Strategy. *IEEE Transactions on Instrumentation and Measurement*. 70: 1–11. https://doi.org/10.1109/TIM.2021.3098388.

[49] Li. Yang, S. You, Y. Tan. 2020. Solid Component Fraction in Multi-phase Flows using Electrical Resistance Tomography and Kalman Filter. *39th Chinese Control Conference*. 6313–6317. https://doi.org/10.23919/ccc50068.2020.9188746.

[50] C. Wu, M. Hutton, M. Soleimani. 2020. Limited Angle Electrical Resistance Tomography In Wastewater Monitoring. *Sensors (Switzerland)*. 20. https://doi.org/10.3390/s20071899.

[51] H. Zhang, C. Tan, F. Dong. 2020. Experimental Investigation of Liquid-solid Two-phase Flow with Electrical Resistance Tomography and Ultrasound Doppler. *I2MTC 2020 - International Instrumentation and Measurement Technology Conference, Proceedings*. 1–6. https://doi.org/10.1109/I2MTC43012.2020.9128814.

[52] R. Kotzé, A. Adler, A. Sutherland, C. N. Deba. 2019. Evaluation of Electrical Resistance Tomography Imaging Algorithms to Monitor Settling Slurry Pipe Flow. *Flow Measurement and Instrumentation*. 68: 101572. https://doi.org/10.1016/j.flowmeasinst.2019.101572.

[53] J. Zhang, H. Li, J. Ma, X. Chen, J. Xu. 2018. Study of the Swirling Flow Field Induced by Guide Vanes using Electrical Resistance Tomography and Numerical Simulations. *Chemical Engineering Communications*. 205: 1351–1364. https://doi.org/10.1080/00986445.2018.1450247.

[54] S. A. Hashemi, R. B. Spelay, R. S. Sanders, B. T. Hjertaker.

2021. A Novel Method to Improve Electrical Resistance Tomography Measurement on Slurries Containing Clays. *Flow Measurement and Instrumentation*. 80: 101973. https://doi.org/10.1016/j.flowmeasinst.2021.101973.

[55] H. Shaban, S. Tavoularis. 2017. Performance Evaluation of Conductivity Wire-mesh Sensors in Vertical Channels. *Flow Measurement and Instrumentation*. 54: 185–196. https://doi.org/10.1016/j.flowmeasinst.2017.02.003.

[56] L. Zhai, J. Yang, Z. Meng, Z. Cui. 2020. Development of Wire-mesh Sensor in Small Bubble Visualization based on Differential Measurement Mode. *I2MTC 2020 - International Instrumentation and Measurement Technology Conference, Proceedings*. 3–7. https://doi.org/10.1109/I2MTC43012.2020.9129032.

[57] S. Ren, H. Liu, C. Tan, F. Dong. 2017. Tomographic Wire-mesh Imaging of Water-air Flow based on Sparse Minimization. *IEEE Sensors Journal*. 17: 8187–8195. https://doi.org/10.1109/JSEN.2017.2752226.

[58] C. Y. Ofuchi, H. K. Eidt, C. C. Rodrigues, E. N. Dos Santos, P. H. D. Dos Santos, M. J. da Silva, F. Neves, P. V. S. R. Domingos, R. E. M. Morales. 2019. Multiple Wire-mesh Sensors Applied to the Characterization of Two-phase Flow Inside a Cyclonic Flow Distribution System. *Sensors (Switzerland)*. 19. https://doi.org/10.3390/s19010193.

[59] K. Sun, Y. Li. 2020. An HDTV-SB Imaging Algorithm for Wire-mesh Tomography. *Measurement Science and Technology*. 31: 045404. https://doi.org/10.1088/1361-6501/ab463f.

[60] M. Sambasivan, S. Gopal. 2019. Handbook of Oil and Gas Piping : A Practical and Comprehensive Guide. CRC Press, Netherlands. https://www.scribd.com/document/403192359/Handbook-of-Oil-and-Gas-Piping-a-Practical-and-Comprehensive-Guide-2019-pdf.

[61] H. Guo, S. Liu, H. Cheng, S. Sun, J. Ding, H. Guo. 2020. Iterative Computational Imaging Method for Flow Pattern Reconstruction based on Electrical Capacitance Tomography. *Chemical Engineering Science*. 214: 115432. https://doi.org/10.1016/j.ces.2019.115432.

[62] B. K. Singh, S. Roy, V. V. Buwa. 2019. Bubbling/slugging Flow Behavior in a Cylindrical Fluidized Bed: ECT Measurements and Two-fluid Simulations. *Chemical Engineering Journal*. 383: 123120. https://doi.org/10.1016/j.cej.2019.123120.

[63] S. R. Aw, W. Azman, W. Abdullah, R. A. Rahim, Y. A. Wahab, M. Hafiz, F. Rahiman, Z. Zakaria, E. J. Mohamed, S. Z. Muji. 2021. Graphical User Interface for Electrical Resistance Tomography System on Static Gas Bubble in a Vertical Metallic Column. 20: 99–102.

[64] C. K. Seong, J. Pusppanathan, R. Abdul Rahim, G. C. Loon, Y. S. L. Susiapan, F. A. Phang, M. H. Fazalul Rahiman. 2015. Hardware Development of Electrical Capacitance Tomography (ECT) System with Capacitance Sensor for Liquid Measurements. *Jurnal Teknologi*. 73: 13–22. https://doi.org/10.11113/jt.v73.4399.

[65] A. E. C. Man, Y. A. Wahab, N. A. TalipYusof, S. R. Aw, M. M. Saari, R. A. Rahim, S. Y. Yu. 2022. Simulation of Frequency Selection for Invasive Approach of Electrical Capacitance Tomography for Conducting Pipe Application Using Oil-Gas Regimes. *IET Conference Proceedings*. 2022: 63–68. https://doi.org/10.1049/icp.2022.2571.