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Developments and applications of electromagnetic tomography in process engineering

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ABSTRACT

In the processing industry, monitoring, control, development and optimization are major performance improving activities. In this industry multiphase mixtures flow within enclosed domains such as process vessels or pipelines, with sometimes complex and harsh process conditions, such as high standards of hygiene or high temperatures and pressures, and require to be monitored and analysed for the purpose of continuous improvements in process control. Electromagnetic Tomography (EMT) is a promising tomographic technique which employs contactless non-invasive inductive sensing coils to evaluate the passive electromagnetic properties of what exists within a sensing domain. Although the potential applications of EMT are widespread throughout various industries such as the medical, environmental, geological and mining industries, this paper focuses on evaluating research focused on applications of this promising technique to the processing arena, with the purpose of identifying research gaps for future evaluation. Research in this area has been divided into two groups based on their purpose: developments in the technique with the purpose of enhancing its capabilities, and exploring the technique's various applications. As one of the more recent tomography techniques, EMT still has a lot of potential remaining to be discovered which would come about with further advancements in its hardware, i.e., sensor unit and excitation unit, and also with improvements in the data processing unit, i.e., data reconstruction. Combining different modalities, which would expand the capabilities of the resulting unit, is an interesting area with high potential, requiring further exploration. EMT remains to be studied in the future on countless other processes, unit operations and media and for several objectives. The application of EMT to other areas such as Food, Dairy, Pulp and paper processes also remain to be developed.

1. Introduction

The necessity of being able to "see" inside optically obscure objects such as medical diagnosis of body parts, evaluating processes inside chemical reactors and detection of faults in underground pipes brought about the idea of tomography (e.g., Stanley and Bolton, 2008; Sharifi and Young, 2022). The main purpose of tomography is to explore material distribution in a region of interest which may be otherwise impossible. This can be achieved by performing a set of non-intrusive measurements through sensors around the periphery and converting the measurements to desirable parameters of interest, e.g. conductivity or concentration (York, 2001).

A wide variety of tomography techniques have been explored to date which can be divided into "hard-field" or "soft-field" tomography. In "hard-field'' tomography, such as X-ray and Gamma-ray tomography, the transmitting signal follows a straight-line pattern. Although these techniques have been extensively applied in the medical arena, they involve very high costs and contain radioactive sources, which is not ideal, especially for extended exposure in the medical field (Wei and Soleimani, 2013).

On the other hand, in "soft-field" tomography techniques, such as Electrical Impedance Tomography (EIT), Electrical Capacitance Tomography (ECT), and Electromagnetic Tomography (EMT) or Magnetic Induction Tomography (MIT), the signal distribution is dependent on the form of the excitation source. Also, the transmitting field no longer follows the straight-line pattern. Due to the increased complexity of the nature of soft-field tomography compared to hard-field, computing the image reconstruction algorithms present much more difficulty. Despite

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this issue, these techniques, which are commonly known as Electrical Tomography (ET) techniques, have attracted a lot of attention recently due to their rapid imaging speeds, fairly low costs, non-intrusiveness and non-hazardous nature. Such properties have made electrical techniques promising for medical imaging of the human body, environmental imaging of underground pollutants, archaeological imaging of submerged remains and especially on-line monitoring and control of industrial processes; e.g. mixing, phase holdup, phase separation and boundary detection (Peyton et al., 1996; Griffiths, 2001; Wei and Soleimani, 2013; Sharifi and Young, 2022).

Among the ET techniques, both EIT and EMT can be applied for conductivity imaging. Although EIT, which is the oldest technique in the electrical tomography group (first reports going back to 1978), is extensively utilized in many applications, it does have a major disadvantage. EIT requires multiple electrodes attached at regular intervals around the surface of and in contact with the imaging object. While to the contrary, EMT has a contact-less feature where the electrodes are replaced with coils located around the imaging object and not in contact with it (Wei and Soleimani, 2013).

In the following sections, after a brief background and introduction to the EMT technique and the data processing required for it, previous research into EMT developments, i.e., sensor unit, excitation unit, and processing unit developments will be discussed. Then the various purposes EMT has been applied to date in the Process Engineering arena will be presented, and conclusions drawn about current and future work.

2. Magnetic induction tomography or electro magnetic tomography

Magnetic Induction Tomography (MIT), also referred to as Electro Magnetic Tomography (EMT), is the most recent and least developed ET technique with the initial reports in 1992–1993 (Griffiths, 2001). As a non-invasive and non-contact imaging method, EMT may have countless potential applications in various fields, such as general separation and mineral processing, tracking or concentration measurements of electrical/magnetic elements in transport and separation processes, and foreign body detection in food processing, textile and pharmaceutical industries. Moreover, examination of metal components for fault detection, imaging ionized water distributions within equipment and pipelines and more generally industrial multiphase flow measurement, chemical abstraction, geological exploration and biomedical research are further EMT applications (Peyton et al., 1996; Sun and Shao, 2013). This technique is sensitive to all three Passive Electromagnetic Properties (PEP) of materials, namely Conductivity, Permittivity and Permeability (Griffiths, 2001).

A typical EMT system mainly includes four basic modules: a sensor unit, an excitation unit, a data acquisition and processing unit, and the image reconstruction and information extraction unit. Fig. 1 demonstrates a basic EMT system (Wei and Soleimani, 2013). The fundamental mutual inductance and eddy current theories are the underlying principles of EMT. A basic description of the process is as follows. With the passing of an alternating current through excitation coils arranged around the object space, a primary magnetic field is formed which creates an electric field. The induced voltage from this electric field can be measured by the detecting sensors/coils. With the presence of a conductive or magnetic object in this field, an eddy current and therefore a secondary magnetic field will be created. In this case, the electric field detected by the sensors will be due to both the primary and secondary magnetic fields. The corresponding voltage measurements are entered into a host computer. By evaluating the variation in the measured induced voltages between the situation when no electric/magnetic object was present (only primary magnetic field) and when such an object was present (primary and secondary fields), and through the use of reconstruction algorithms, an image of the internal material distribution can be reconstructed (e.g., Sun and Shao, 2013; Ma and Soleimani, 2017). Fig. 2 demonstrates a photograph of an EMT system with visible coils set for measurement of aluminium rod samples 10 mm in diameter and 100 mm in length, with a 105 mm diameter circular sample space [1].

3. Data processing

All electrical tomography techniques require the solving of two diverse problems: the forward problem; and the inverse problem.

3.1. The forward problem

The forward problem is a simulation study that predicts the voltage or current distribution on all sensors from a known PEP distribution. In EMT, the differential forward model is expressed in terms of Maxwell's equations and eddy current equations. Linear image reconstruction can be applied for imaging simple and highly symmetrical objects. Where a more accurate image is required, the Finite Element Method (FEM) is applied which can deliver a general solution for the evaluation of the field distribution in the forward problem. A sensitivity matrix that demonstrates the disturbance in the receiving voltage due to the changes in the electrical properties of the imaging subject can then be derived (e.g., Wei and Soleimani, 2013; Ma and Soleimani, 2017).

3.2. The inverse problem

The inverse problem produces the best estimation of the unknown

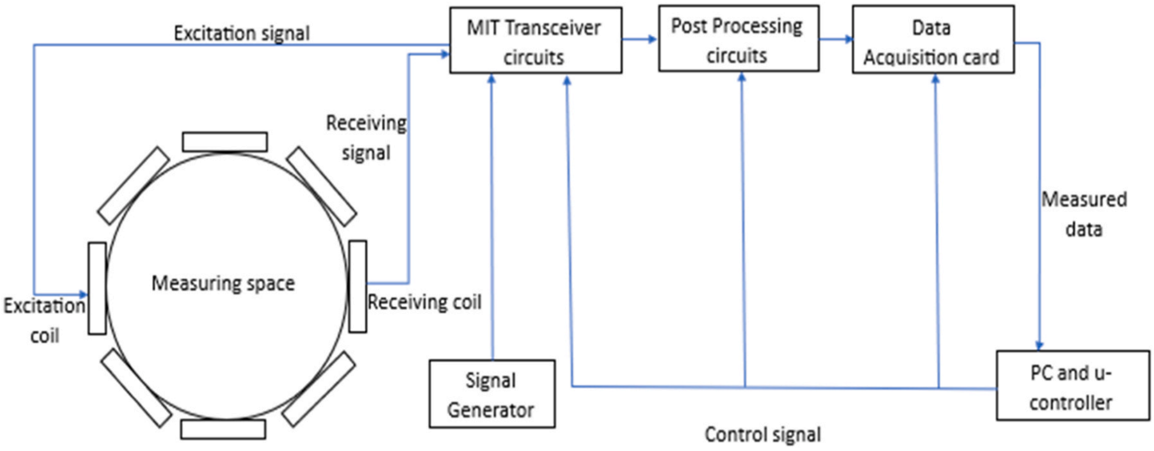

Fig. 1. Block diagram of a complete EMT system, adapted from (Wei and Soleimani, 2013).

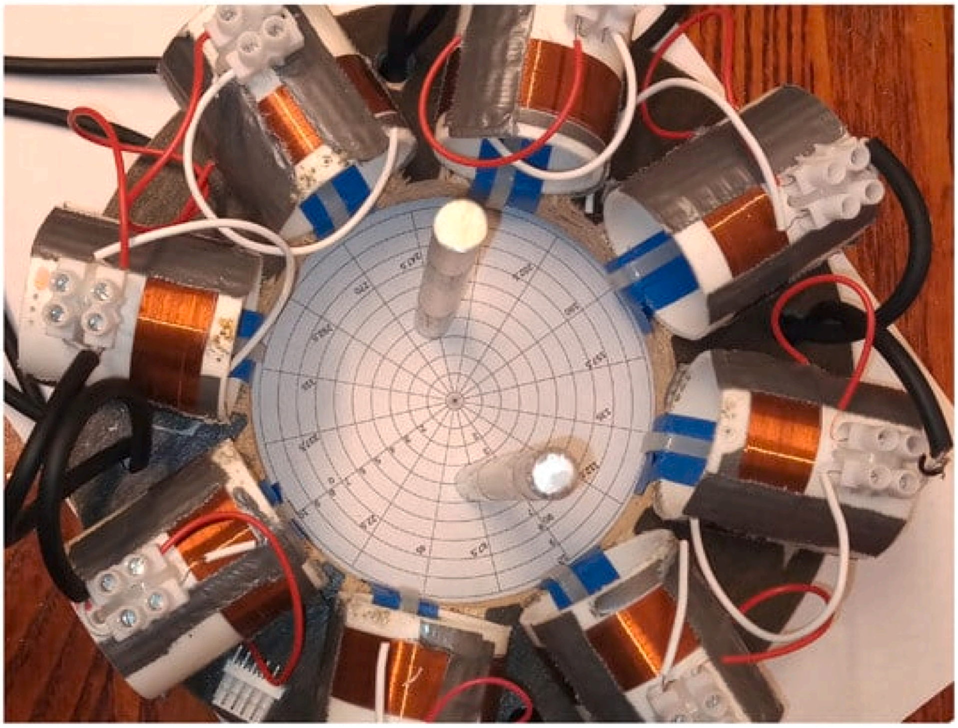

Fig. 2. Photograph of an EMT system with visible coils set for measurement of aluminium rod samples 10 mm in diameter and 100 mm in length, with a 105 mm diameter circular sample space (Dingley and Soleimani 2021).

PEP distribution of the object space using the known physical sensor measurements. When the forward model is simulated, the inverse solver or sensitivity matrix will be used to create a reconstructed image of the PEP distribution of the object field. In EMT this process of image and data reconstruction is more complex due to two issues. Firstly, as the electromagnetic transmitting field is dispersed and does not follow a straight line, the conductivity variation is no longer "localized" and therefore could create signal disturbance on any measurement set. Secondly, the inverse problem in EMT is an ill-posed problem as the number of pixels with unknown conductivity is commonly larger than the number of measurements and any small disturbance from the sensor reading can cause large disturbance in the solution. These difficulties in the EMT inverse problem and the stabilization techniques applied to transform the ill-posed problem to a more well-posed problem are the focus of a large portion of EMT literature (Wei and Soleimani, 2013). Fig. 3 demonstrates an example reconstructed tomogram of a 5 % saline bottle located on the right hand side (a) and another tomogram of a 5 % bottle on the left and a 3 % bottle on the right (b) [2].

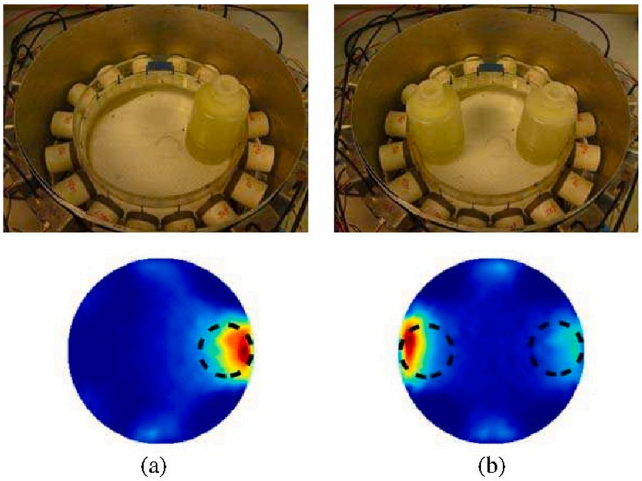

Fig. 3. Reconstructed images of (a) one 5 % saline bottle located at the right hand side and (b) one 5 % bottle at the left and one 3 % bottle at the right (Wei and Soleimani 2012).

The research around EMT to date generally has two overall foci. A large proportion of the research has focused on advancements in various aspects of EMT; such as developments in the sensor unit, the excitation unit and the data acquisition and processing units, with the purpose of producing more accurate measurements and therefore advanced knowledge in a specific field. Some more recent literature has focused on applying this novel technique to particular applications and making use of its various advantages in order to provide better knowledge into processes or situations previously not possible. This paper reviews and brings together all EMT related literature presenting developments and applications in the chemical and process engineering arena. Fig. 4 demonstrates a flowchart of the breakdown of such research.

4. Electromagnetic tomography developments

4.1. Sensor unit developments

As data attained by the sensors provides information from the object field, EMT sensors play a vital part in the entire system. Research into EMT was initiated in the late 1980's with the thought of applying it to medical imaging of the body. The initial sensor systems proposed were very simple, applying only two coils, one working as the excitation coil, and the other working as the detection coil. The objects were positioned on a sliding turntable moving perpendicular to the axis of the coils. Printed Circuit Board (PCB) coils were later introduced using both a flat rectangular coil and a gradiometer comprising two co-planar, counter–wound PCB coils as the detection coils. An additional coil was located behind the source to provide a reference signal to calculate the phase difference of the detector signal (Liu and Dong, 2008). Later, a large portion of EMT related research focused on further improvements in the sensor unit which is discussed in the following sections. Table 1 shows

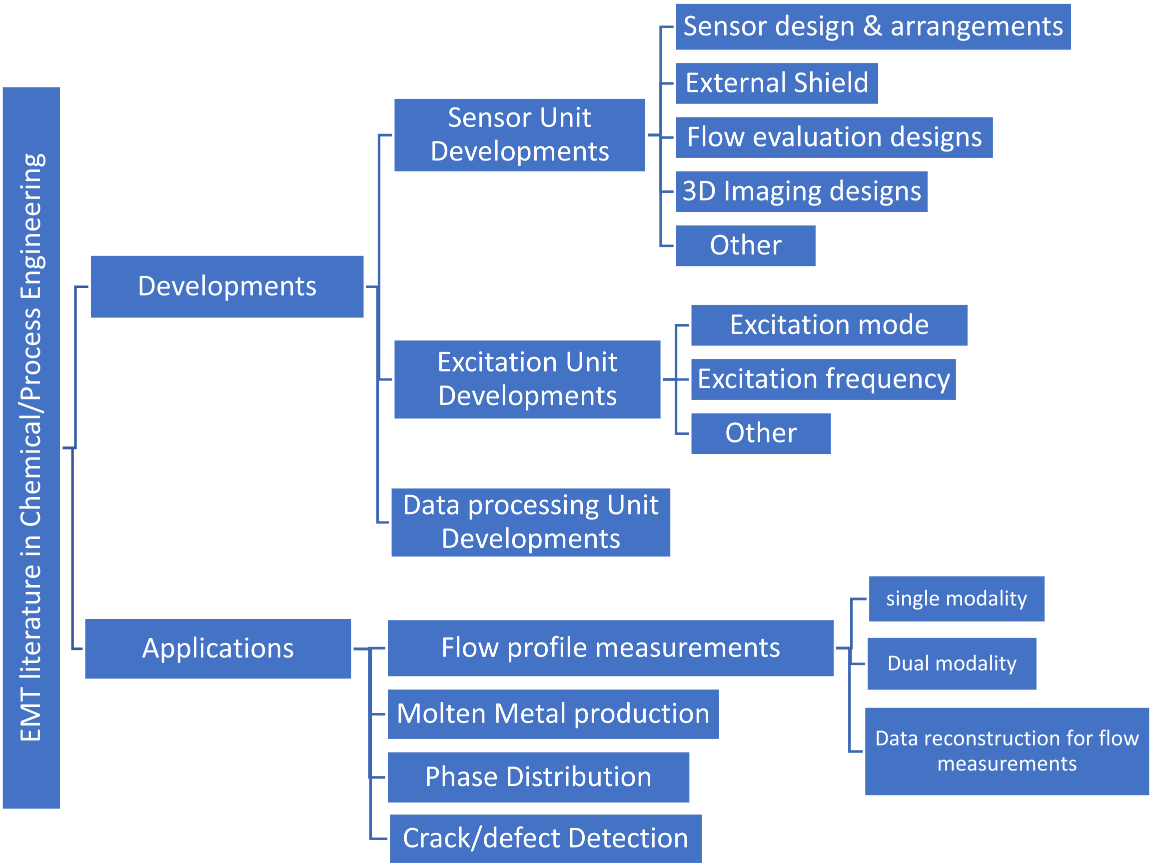

Fig. 4. Flow chart for EMT literature in Chemical/Process Engineering.

categorized with this focus in the Chemical Engineering area.

4.1.1. Developments in sensor design and arrangements

One of the main issues with tomography imaging techniques in general, and EMT in particular, is the lower resolution at the centre of the imaging space. Thus, with the purpose of improving the detectability at the centre of the object space, Yu et al. (1998) designed and presented a nonintrusive system with a rotatable parallel uniform excitation magnetic field. To condition the output signals from the sensor, the vacant space background field measurements were deducted and subsequently the overall dynamic range of the data acquisition system was increased. The feasibility of using a planar EMT sensor and measurements from only one surface to study the distribution of electrically conductive bars was studied next (Ramli and Peyton, 1999).

Circular or near-circular array-based systems were initially introduced using 16 coils assemblies. In addition to medical imaging, EMT systems also started being introduced to industrial fields. Planar and parallel sensor systems were purposefully designed for this field. Another issue which is specific to EMT is that the primary magnetic field is much greater (10^2 to 10^6 times) than the desired secondary field. The large primary field signal confines the accuracy to which the minor secondary signal can be measured. In order to resolve this issue, a few approaches (back-off coils and gradiometers) have previously been presented to decrease the sensitivity of the measurement coils to the primary field. In 2005 a group of researchers presented an alternate tactic in which the measurement coils were positioned with their axis in the plane of the excitation coil. With this orientation no primary voltages will be induced as the primary field from the excitation coils will cut the axes of the measurement coils at right angles and hence no net flux will pass through them (Igney et al., 2005). Igney et al. (2005) developed and examined a planar-array EMT system with four printed excitation coils of four turns which were shielded, eight surface-mount inductors of inductance 10 μH as sensor and a calibration coil to yield a solid primary field. A Signal-to-Noise Ratio or SNR of 47 dB was achieved at 4 MHz for their experimental setup. A novel sensor system was later proposed and further developed for the purpose of detecting faults on a thin metallic plate in which six cylindrical coils were spread forming a circular array with their axes perpendicular to the plate under inspection instead of the traditional parallel. In comparison to the conventional EMT sensor arrangement, in this novel design the planar sensors are more effectively coupled through samples rather than directly. This new arrangement of sensors was able to provide more sensitivity, especially in situations where only one surface of the testing metal plate is accessible, as for many non-destructive testing applications (Yin and Peyton, 2005; Yin and Peyton, 2006; Yin et al., 2007).

The effect of variations in numbers and locations of excitation and detection coils on the 3-dimensional EMT resolution and displacement of an inhomogeneity has been investigated, demonstrating that EMT image resolution does depend on the applied coil arrangement, particularly the position of the coils in relation to each other, and improves closer to the border of the object (Merwa and Scharfetter, 2007). The effect of EMT sensor size (coil diameter) and location has also been simulated using COMSOL software based on sensitivity to conductivity and signal/carrier ratio, further elaborating that optimum design of sensor array would provide for attaining extensive knowledge of the sensing domain (Liu and Dong, 2008). An EMT system with significantly improved phase-measurement stability has been introduced with sensors responsive to the primary field and systems applying gradiometer sensors. The novel method demonstrates potentially high precision / low frequency EMT systems, without the need for gradiometers, which could also be especially applicable to long-term monitoring applications (Watson et al., 2008). COMSOL and Finite Element Analysis have been used in order to level the sensitivity distribution of the sensing volume with the purpose of producing similar signal intensities for electrically

Table 1
References for EMT sensor unit developments.

EMT Sensor Unit Developments	Developments in sensor design & arrangements	(Yu et al., 1998) (Ramli and Peyton, 1999) (Peyton et al., 1999) (Igney et al., 2005) (Yin and Peyton, 2005) (Yin and Peyton, 2006) (Yin et al. 2007) (Merwa and Scharfetter, 2007) (Liu and Dong, 2008) (Watson et al., 2008) [3] (Dita Ayu et al., 2018)
	Developments in external Shield	(Peyton et al., 2003) (Junqing et al., 2010) (Wang et al., 2011) [4]
	Developments for flow evaluation	(Wang and Gong, 2006) (Abrolat and Musch, 2017b) (Abrolat and Musch, 2017a) (Vauhkonen et al., 2018)
	Developments for 3D imaging	(Liu et al., 2020) (Yue et al., 2020) (Yue et al., 2021)
	Other developments	(Park and Kim, 2005) (Wee et al., 2008) (Wood et al., 2017) (Cui et al., 2018) [5] [6]

conductive objects further away from the transmitting and receiving units and close to them. Results demonstrate that compared to the common one-excitation coil systems, the sensitivity of a EMT -System can be enhanced six-fold when a second excitation coil is applied (Dastjerdi et al., 2015).

Optimal sensor design for imaging metal objects was investigated, in which parameters being tested for defining an optimal sensor design were: transmitter-receiver distance; and frequency of transmitter signal. The ideal transmitter-receiver coil distance was determined to be the shortest, whereas the ideal transmitter signal frequencies were at both 5 MHz and 9 MHz. Based on the optimum parameters obtained, a multi-channel EMT sensor was designed with four transmitter coils and four receiver coils which were positioned around a circle, with each transmitter and receiver pair placed opposite to each other (Dita Ayu et al., 2018).

4.1.2. Developments in external shield

In order to efficiently decrease capacitive couplings of an EMT system and prevent the effect of exterior fields which are larger and more prominent than the signal produced by the subject itself, an external shield is required in an EMT setup. The effects of an external electromagnetic shield including the diameter and height of the shield on the sensitivity maps and background signals of an EMT system have been studied using simulations and experimental data. It was concluded that with the increase of height and decrease of diameter, the dynamic range of signal between coil pairs increases (Peyton et al., 2003). The effect of the material, height and inner radius of a non-magnetic shield on the shielding effect based on simulation models and optimization criterion, were also later investigated (Junqing et al., 2010; Wang et al., 2011). A novel conductive shield has also recently been designed with the purpose of shielding the outer area of the system from the magnetic field while supporting system performance. This novel design has been applied for the conductive shield in an EMT system (Seo et al. 2022).

4.1.3. Developments in sensor design for the purpose of flow evaluation

Instead of the conventional transverse magnetic field in Electromagnetic Flow meters, the practice of using multiple electrode pairs which can be applied for the reconstruction of the multiphase flow profiles was introduced in 2006. The correlation between induced electric potential or potential drop with the conductive continuous phase velocity distribution of multiphase flow in pipe using EMT was effectively demonstrated by Wang and Gong (Wang and Gong, 2006). Later a novel approach to velocity profile measurement was proposed and evaluated with a new sensor design in which magnetic field coils are used in a ferromagnetic circuit and are positioned on the measuring tube perimeter. The employment of a ferromagnetic circuit would allow smaller coil size and excitation current and therefore a high density of magnetic poles and huge variability of the magnetic field could be accomplished (Abrolat and Musch 2017b; Abrolat and Musch 2017a). In order to improve EMT flow measurement accuracy for asymmetric flows, e.g., in multiphase flows, pipe elbows and T-junctions, application of several excitation coils (four) and measurement electrodes (sixteen) have been successfully applied. The study proves that application of a multiple sensor and detector EMT system, together with appropriate velocity field reconstruction approach, will provide reliable velocity field estimates (Vauhkonen et al., 2018).

4.1.4. Developments in sensors for 3D imaging

3D images in comparison with 2D images, are able to present more information about the distribution of electromagnetic properties; conductivity, permittivity and permeability, and demonstrate the spatial assembly of subjects with more info in the z-direction compared to cross-sections with 2D images. The direct 3D EMT imaging technique has been recently introduced with measurements obtained from the same and different layers of sensors (Liu et al., 2020). Within the study various issues including 3D sensor layout, measurement strategy, simulation research, and image reconstruction algorithm have been investigated. The sensor system is designed so that twelve coils are evenly distributed around three four-coil planes with each plane rotated 45° compared to the previous plane (Liu et al., 2020). Simulation studies, using FEM software, of various sensor models with different sensor layers and different number of coils confirm the feasibility of 3D reconstruction in multi-layer sensor EMT (Yue et al., 2020). Employing the movement of a single layer sensor array along the z-direction during the data collection process, for the purpose of building a 3D image, has been proven to be ineffective due to the need for a very slow movement speed. On the other hand, a novel method, in which the reconstructed single Layer 3D- EMT image with a 3D sensitivity map, was demonstrated to be a successful technique to save on hardware resources while getting the reconstructed images of 3D views (Yue et al., 2021).

4.1.5. Other sensor system developments

In 2005, Park and Kim developed an EMT system and evaluated the effect of variations in the relative permeability, size and location and movement of the sensed object on the signals of the EMT system using a non-linear finite element method. Experimental data and simulated data presented good agreement, demonstrating for relative permeability as low as 10, detection of size and location of the object was possible with the developed EMT system (Park and Kim, 2005). Research into improving phase noise and long-term phase stability was also conducted by Wee et al. in which a multi-frequency EMT system with minimal phase noise and high long-term phase stability was designed (Wee et al., 2008). The functionality of an entirely automatic magnetic imaging system with the ability to construct 2-D images of presented metallic objects ranging from manganese with electrical conductivity of less than 1 MS/m, to copper shields approaching 60 MS/m has also been studied. The study evaluated the feasibility of classifying different material from conductivity maps and also the effect of various shielding conductivity material on image resolution (Wood et al., 2017). An electromagnetic tomography system based on a commercial LCR (Inductance (L), Capacitance (C), and Resistance (R)) meter (or impedance analyzer) has been demonstrated to be able to accomplish multi-channel mutual inductance measurements by integrating the LCR meter with a custom-made programmable analogue switch array. This novel system was able to provide enhanced accuracy and repeatability (Cui et al., 2018).

Recently Feldkamp presented a paper focused on quantifying the weight of parasitic capacitance and correlated losses when working with single inductive sensor EMT systems. For such single-coil EMT systems, it is demonstrated that the coil is generally positioned within 2 cm of the target boundary, and a correction is offered to provide more accuracy in the measurement of true inductive loss (Feldkamp, 2022). A novel miniaturised EMT system has also recently been developed with a multi-channel phase-domain transceiver integrated circuit for automatic high-resolution phase measurement and wireless connectivity, which has provided for improved power productivity and miniaturization. The developed system has successfully performed non-destructive testing for the detection of various size cracks on carbon fibre rods (Jeon et al., 2022).

As discussed in this section, although research has been conducted for development of the sensor system, further studies in this area with the purpose of optimizing the sensor system geometry and arrangement which may be specific to each application purpose, will be able to provide for more accurate and precise measurements. Also, research into understanding the measurement limitations in terms of detection sensitivity based on sensor system characteristics would be highly beneficial for process monitoring purposes. The scale-up of all such evaluations and findings to commercial scale plants would be the ultimate goal, and is therefore also an area requiring evaluation.

4.2. Excitation unit developments

As one of the essential parts of the EMT system is the sensor array, and the excitation signal is applied directly to the sensor array, the excitation strategy, together with the frequency and amplitude of the excitation signal, determine the quality of the information obtained from the subject, as well as accuracy of the information post extraction from the imaging space (Yan et al., 2011). Therefore, Table 2 categorizes these references and the following section will concentrate on discussing literature with a focus on excitation unit developments.

4.2.1. Excitation mode developments

In 1996, three diverse EMT systems focusing on varying excitation modes were presented and several different image reconstruction techniques investigated by Peyton (Peyton et al., 1996). Later, the parallel excitation mode, with the novelty of using a flexible circuit strips array, was studied and the excitation sensing field together with the empty sensing field were simulated using the finite element method (FEM), with the purpose of investigating the interaction between the alternative excitation field and the measured subject (Liu et al., 2005).

Table 2
Categorized references for EMT excitation unit developments.

EMT excitation unit developments	Excitation Mode Developments	(Peyton et al., 1996) (Yu et al., 1998) (Liu et al., 2005) (Fu et al., 2011) (Liu et al., 2004) (He et al., 2014) (Ke et al., 2018)
	Excitation Frequency Developments	(Li et al., 2009) (He and Xu, 2011) (Yan et al., 2011) (Fu et al., 2013)
	Other Excitation Developments	(Maimaitijiang et al., 2007a) (Maimaitijiang et al., 2007b) (Liu et al., 2009) (Zhang et al., 2010) (Wang et al., 2011) (Dastjerdi et al., 2015)

Fu et al. (2011) used Finite Element simulation in COMSOL software to study various excitation strategies based on the number and position of the excited coils: Single excitation, in which one coil is excited while all others are detecting; Adjacent excitation, in which two adjacent coils are being excited while all others are detecting, and opposite excitation in which two opposite coils are being excited while all others are detecting. The single excitation strategy was presented as having extensive coverage, fewer errors, and sturdiness of registration in noise, while the opposite excitation provided better image reconstruction in the centre part, because of the well homogenized sensing field distribution, and encouraging sensitivity at the centre of the sensing field.

An orthogonal signal demodulation method which uses two phase adjustable orthogonal vectors has been demonstrated to demodulate the boundary magnetic signals of EMT sensors, effectively and rapidly (Liu et al., 2004).

Various excitation modes were compared in a specifically built multi-excitation EMT system demonstrating a quasi-parallel excitation structure, producing improved quality reconstructed images due to the more independent projections and evenly distributed sensitivities compared to the parallel and coil-pair modes (He et al., 2014).

A productive sector EMT data detection approach has recently been presented in which the fan-shaped recognition method has been applied for verification and analysis. Results demonstrate extensive improvement in the detection data by successfully applying the fan-shaped rotation method (Ke et al., 2018).

4.2.2. Excitation frequency developments

Investigation into various factors of the object field in EMT such as object internal composition, relative position, relative size and excitation frequency has been performed, demonstrating that larger conductivity and larger size objects produce more noticeable eddy currents which are unrelated to the locations. With a higher angular frequency, the subject characteristics could not be detected as the skin depth would be too small in comparison with metal's thickness to produce eddy current (Li et al., 2009). The optimal excitation frequencies for certain subjects were investigated through theoretical analysis and it was discovered that the optimum frequency for studying high conductivity subjects (e.g. copper) should be at a magnitude of kHz while for low conductivity subjects (e.g. saline) the optimum frequency should be set to 10 MHz (He and Xu, 2011). The finite element simulation software, COMSOL Multiphysics, was applied by Yan et al. to evaluate the excitation approach and the excitation frequency of electromagnetic tomography with the purpose of strengthening the sensitivity of the sensor array to the changes of the object field distribution, enhancing the sensitivity and precision of the system and assuring highly accurate and stable experimental data. Results demonstrate increasing the distance between excited and detected coils decreases output voltage and the primary magnetic field effect (Yan et al., 2011). Using the same software and through experiments, the direct effect of variations in the EMT excitation condition on the receiving signals and on the sensitivity through receiving signals, have been studied. Results demonstrate, in multi-coil excitation strategy increasing the number of coils will improve performance and with higher excitation frequencies higher signal would be received (Fu et al., 2013).

4.2.3. Other excitation unit developments

Simulation time was found to be reduced by implementing parallelization of an EMT forward model on a personal computer workstation cluster. The parallelization was performed by either splitting the problem by different excitation and detection coils or by dividing the physical space into several layers (Maimaitijiang et al., 2007a). The study was further expanded by performing a comparison between three parallelization methods of: splitting by different coils using a distributed memory approach; splitting by physical domain decomposition using both distributed and shared memory, and splitting by both coil and physical domain using distributed and shared memory approaches correspondingly. Due to low inter-processor communication requirements, results demonstrated the distributed memory parallelization by coil as the most efficient method while it is limited by the number of coils within the EMT system (Maimaitijiang et al., 2007b).

An EMT system in which the excitation signal generation and measurement signal demodulation were both attained by applying an integrated impedance analyzer integrated circuit controlled by an embedded microcontroller, has been developed. In this system the sensor was built with a parallel excitation layer, which is realized with flexible circuit strips as current sources, and a coil detector array. This study has proven EMT applicable as an embedded system suitable for industrial environment requirements (Liu et al., 2009).

An EMT system in which the generation of the excitation signal, the control of the external circuitry and the digital demodulation are all executed by a Field Programmable Gate Array FPGA is presented with the purpose of performance improvement. Analysis is performed to evaluate the impact of the excitation signal frequency, the sample frequency and the accumulation number of the Media Access Control (MAC) Internet Protocol (IP) core on the demodulation, resulting in improved system integration and decreased debugging difficulty (Zhang et al., 2010). The study was further expanded with evaluation of the effect of the material, height and inner radius of a non-magnetic shield based on the uniformity criterion of sensitivity. A direct digital synthesizer module, digital demodulation module, Multipoint Control Unit (MCU) module, Digital to Analog (DA) interface module, Analog to Digital (AD) interface module and USB communication module were all integrated in an FPGA chip (Wang et al., 2011).

As the excitation unit directly applies signals onto the sensor unit, similar to the sensor unit developments, further advancements within the excitation unit would provide for better accuracy and precision of the measurements and as a result more applicability for the EMT technique. Finding optimum excitation mode and frequency which could be specific to sensor system characteristics and application purpose would be very beneficial. Again, understanding excitation unit characteristics applicable to large commercial size plants would also assist reaching the final goal of applying EMT to commercial plant monitoring and control.

4.3. *Processing unit (image reconstruction and information extraction) developments*

The primary aim of the processing unit is the solving of the inverse problem introduced in Section 3.2. The goal is to reconstruct the unknown PEP distribution as, for example, a conductivity (or current density) map of a cross-section of the object field. This is accomplished by combining the measurements from multiple detection coils and taking advantage of the geometry of how these coils are arranged around the object field to solve the inverse problem of Section 3.2.

4.3.1. *Image reconstruction fundamentals*

The Biot-Savart law describes the magnetic field generated by electrical current flow and is the basis of the forward problem.

$$B(r') = \frac{\mu_0}{4\pi}\int_V \frac{J(r)\times(r-r')}{|r-r'|^3}dV \tag{1}$$

In Eq. 1, $|r - r'|$ represents the distance between the source $J(r)$ and the measurement $B(r')$ and μ_0 is the permeability of free space. Since we can only measure the magnetic field $B(r')$ at a finite number of locations we discretise the integral equation into a system of linear equations with the following matrix formulation.

$$\boldsymbol{Fj} = \boldsymbol{b} where \boldsymbol{F} \in \mathbb{R}^{m\times n} \quad \boldsymbol{j} \in \mathbb{R}^{n} \quad \boldsymbol{b} \in \mathbb{R}^{m} \tag{2}$$

In Eq. 2, each element of the $(n \times 1)$ vector j corresponds to the current density $\boldsymbol{J}$ at a point on a grid covering the region of interest and $\mathbf{F}$ is a $(m \times n)$ sensitivity matrix specifying the relationship between the current j and magnetic measurements $\boldsymbol{b}$, where $\boldsymbol{b}$ is a $(m \times 1)$ vector of measurements of B_T.

In order to perform the image reconstruction, we need to solve the inverse problem which involves finding the best estimate $\hat{j}$ of the unknown current density j from measurements of the magnetic field. This is an ill-posed problem and it is known that no unique solution exists (Rainer et al., 2002).

For this kind of problem, classical methods fail to give meaningful results and various numerical techniques have been developed to find the best estimate of $\hat{j}$ given the magnetic field measurements. The simplest technique commonly used to find the minimum least-squares solution is to make use of the pseudo-inverse also known as the Moor-Penrose inverse.

The pseudo-inverse uses the singular value decomposition (SVD) to generate the approximation of the inverse by decomposing the matrix in the following form.

$$\boldsymbol{F} = \boldsymbol{USV}^T = \sum_{i=1}^{n} u_i \sigma_i v_i^T \quad \boldsymbol{U} \in \mathbb{R}^{m\times n}, \quad \boldsymbol{S} \in \mathbb{R}^{n\times n}, \quad \boldsymbol{V} \in \mathbb{R}^{n\times n} \tag{3}$$

In Eq. 3, $\mathbf{U} = (u_1, u_2, \ldots, u_n)$ and $\mathbf{V} = (v_1, v_2, \ldots, v_n)$ are matrices with orthonormal columns. The matrix $\mathbf{S} = diag(\sigma_1, \sigma_2, \ldots, \sigma_n)$ contains the singular values of the matrix as the diagonal elements organised in non-increasing order. This decomposition can be applied to the sensitivity matrix $\mathbf{F}$ and the resulting orthonormal columns of $\mathbf{U}$ and $\mathbf{V}$ can then be used to calculate the approximation of j as

$$\hat{j} = \sum_{i=0}^{n} \frac{u_i^T b}{\sigma_i} v_i \quad u_i^T \in \mathbb{R}^{1\times m}, \quad b \in \mathbb{R}^{m}, \quad v_i \in \mathbb{R}^{n} \tag{4}$$

Notice that this approximation is a linear combination of the orthonormal basis vectors v_i. The ill-conditioned nature of this solution can be analysed by looking at the size of the singular values σ_i. Since the values are ordered, for increasing values of i the very small values of σ_i start to dominate the sum. The corresponding values for $u_i^T b$ tend to oscillate in sign when measurement noise is present which degrades the solution to the point where reconstruction is impossible. Therefore, to provide a meaningful solution the small singular values must be dealt with by using some form of regularisation.

Tikhonov described and popularized the classic regularisation technique in 1963 (Tikhonov et al., 1977). The goal here is to deal with the small singular values that start to dominate the solution of $\hat{j}$as i grows. There are various approaches based on the elimination of the small singular values and the simplest approach, known as the truncation method, simply keeps the largest k values and sets the remaining values to zero. However, knowing what value to set k as for optimal reconstruction quality is problematic.

Tikhonov's method involves damping down the effect of small singular values by adding a so-called *filter factor* f_i to the solution of $\hat{j}$ so that as the singular values σ_i decrease, the f_i values tend to zero such that the contribution of smaller σ_i are effectively filtered out of the solution.

$$\hat{j} = \sum_{i=0}^{n} f_i \frac{u_i^T b}{\sigma_i} v_i where f_i = \sigma_i^2 \Big/ (\sigma_i^2 + \lambda^2) \tag{5}$$

This solution generally gives good approximations of the unknown current density based on the magnetic field measurements but there are many other approaches, and this is an active area of research.

4.3.2. *Image reconstruction developments*

There has been a lot of interest in the optimisation of the image reconstruction algorithm over the past two decades. The main focus has been to improve the speed of calculation while maintaining a level of accuracy that results in a practically usable reconstruction. Efficient reconstruction algorithms that can perform reconstruction in real-time enable practical use in both medical and industrial applications. This section is organised as a taxonomy of reconstruction methods organised into four broad categories: Direct methods, Regularisation methods, Iterative methods, and Machine learning-based methods. The aim is not to be an exhaustive review of all the literature in each category, but rather to highlight the most influential advances.

4.3.2.1. Direct methods. One of the original and most basic approaches to the reconstruction of the unknown current density is to directly estimate the inverse of the sensitivity matrix from Eq. 1 by recognising that this matrix is also the Jacobian matrix that describes the sensitivity of the measurements to changes in the current density. In the method suggested by Kotre in his *linear back projection (LBP) method* the normalised transpose of the Jacobian is used as the approximation to the inverse and applied to the measurements directly to produce the current density. This method is computationally very efficient but suffers from poor reconstruction quality as it tends to multiply the effect of noise that is present in any realistic measurement.

Due to these limitations the LBP method is not used often in realistic applications, but several improvements to the way that the sensitivity matrix gets calculated or filtered have resulted in ways to improve the speed and accuracy of this method. For example, Huo et al. presented a way to decrease the dimension of the sensitivity matrix to improve the speed of calculation without significantly affecting the reconstruction accuracy (Huo et al., 2020). Their idea is similar to the SVD decomposition of the sensitivity matrix and then keeping only the columns of the decomposition associated with the largest singular values. However, they reduce the dimension by focussing on the covariance of matrix S and filtering out the dimensions that have the smallest variance. This leads to a saving in processing time of almost 30 % with very little loss in reconstruction quality.

Similarly, Sun et al. presented improvements to the LBP algorithm (Sun et al., 2015). They present a data decomposition method, also based on the filtering of the sensitivity matrix, that improves the spatial resolution of the reconstruction compared with a LBP reconstruction that does not use their method. They use both simulated data and experimental data to validate their method and show a 15 % reduction in reconstruction error compared with the original LBP algorithm without sacrificing computational complexity.

Specialised direct methods of solving the inverse problem without filtering of the sensitivity matrix exist for constrained problems. For example, in their paper Tamburrino et al. rely on the monotonicity property of reconstruction problems that involve two-phase materials to directly calculate the unknown current density from the measurements (Tamburrino et al., 2003). They use simulated data to show that their method can successfully reconstruct and identify shapes from noisy data.

4.3.2.2. Regularisation methods. As we have mentioned in Section 4.3.1, it is necessary to add some form of regularisation to the inversion of the sensitivity matrix in order to get sensible results, as the matrix is very ill-conditioned. Regularisation is required for both the direct methods of Section 4.3.2.1 and the iterative methods of Section 4.3.2.3, so the choice how this is done is key to the reconstruction process.

As already mentioned, Tikhonov's method is the classic approach here and is based on the damping of the small singular values of the sensitivity matrix. However, the filter factor used to damp these factors can be modified to better suit specific applications and can be chosen to be more accurate at the expense of calculation speed or vice versa.

Total variation regularisation (TVR) aims to improve on the edge-preserving quality of the reconstruction and was originally proposed as a noise removal technique in image processing (Rudin et al., 1992). The application of TVR for image reconstruction in electrical impedance tomography was demonstrated by Borsic et al. and illustrated the method's ability to reconstruct sharp boundaries (Borsic et al., 2010). This is particularly useful in image reconstruction where discontinuities are expected in the unknown current density and where the exact location of these discontinuities are critical to the application. For example, in medical tomography the exact location of inter-organ boundaries requires sharp reconstruction of the conductivity map with edges clearly defined.

TVR uses a L1 norm to regularise the inversion process instead of the standard quadratic L2 approach. This has the advantage of not biasing the solution to smoothed discontinuities but also makes the objective function to be minimised non-differentiable. In order to solve the regularised optimisation problem, probabilistic or iterative methods are often used. For example, one of the earlier approaches to solve the problem of TVR leading to a non-differentiable function is to replace the absolute value function that characterises the L1 norm with a polynomial in the neighbourhood of zero. This technique was used by Rudin and Dobson in their deterministic framework for noise removal (Rudin et al., 1992; Dobson and Santosa, 1996). Chan and Mulet (1996) proposed a more efficient method for dealing with the non-differentiable objective function based on the primal-dual theory. This leads to an iterative Gauss-Newton approach to the nonlinear inversion of the sensitivity matrix.

4.3.2.3. Iterative methods. As an alternative to direct regularisation, iterative regularisation methods often have a computational advantage that lets one iterate until sufficient accuracy for the application has been achieved, as opposed to calculating the maximum precision solution. The classic iterative method is called Landweber iteration which was originally developed for well-posed least squares optimisation problems but has been adopted for solving the linear inverse problems found in tomography applications (Yang et al., 1999).

Landweber iteration approximates the solution to Eq.2 as a linear minimisation problem:

$$\min_j \| Fj - b\|_2^2 \Big/ 2 \tag{6}$$

The iterative update to converge to j is

$$j_{k+1} = j_k + \omega F^T (b - Fj_k) \tag{7}$$

Where ω is the relaxation factor that satisfies $0 < \omega < 2/\sigma_1^2$ and σ_1 is the largest singular value of F. A major disadvantage of this method is the slow rate of convergence. Because of this, it is not used in most practical applications. Hypothetically, if the sensitivity matrix was orthogonal this method could have an optimal convergence rate but since these matrices are typically ill-conditioned and underdetermined this is not the case which leads to the inverse of F being approximated crudely as F^T.

Tikhonov regularisation can be combined with Landweber iteration to vastly improve the convergence rate by replacing the relaxation factor with $(F^T F - \lambda I)^{-1}$ which leads to iterative Tikhonov regularisation.

$$j_{k+1} = j_k + (F^T F - \lambda I)^{-1} F^T (b - Fj_k) \tag{8}$$

The conjugate gradient (CG) method is another iterative method suited to solving linear systems, like that of Eq. 1, and is particularly well suited to solving large sparse systems that make direct methods impractical, for example, the inverse problem of EMT (Saad, 2003). The method has the advantage of theoretical guaranteed convergence to the solution in a fixed number of iterations but practically this solution is never obtained since the method is numerically unstable. Instead, a required tolerance is chosen and this method is generally able to reach a given tolerance after a small amount (compared to the problem size) of iterations. It is often faster than gradient descent or Newton's method and does not require the calculation of the Hessian matrix which can be computationally expensive. However, this speed is usually sensitive to the preconditioning done on the sensitivity matrix. Selection of this appropriate preconditioner is problem-dependant and can be difficult.

The CG method has been successfully applied to EMT as it is well suited to fast reconstruction when the sensitivity matrix is large and sparse. Liu et al. showed that a modified version of CG converges faster than Landweber and an unmodified CG and also produces a more accurate reconstruction with better localisation of test targets (Li and Shao, 2011; Liu and Zhan-Jun, 2013; Wang and Li, 2013). The CG method was also used in a simulation study to perform a 3D reconstruction of test data to demonstrate non-contact volumetric imaging using multiple layers of sensors (Yue et al. 2020).

The Simultaneous Iterative Reconstruction Technique (SIRT) is an iterative method that alternates between forward and backwards projection to approximate the unknown current density j. The update equation is similar to the Landweber equation but uses a different factor where the relaxation factor is found in the Landweber equation.

$$j_{k+1} = j_k + CF^T R(b - Fj_k) \tag{9}$$

where C and R are diagonal matrices that contain the inverse of the sum of the rows and columns of the sensitivity matrix F. They act as normalising factors to compensate for the number of pixels in the current density map affected by each excitation unit.

This method has become popular in the imaging of steel girders, steel pipes and molten metals during casting. For example, Binns et al. presented a method to monitor the flow of molten metal by using EMT and used SIRT to reconstruct the conductivity map that indicates the location of the flowing metal (Binns et al., 2001). Bissessur and Bhurtun presented a method to image steel-reinforced bars embedded in concrete or other non-conducting materials using a planar EMT approach. Similar to the paper from Binns et al., SIRT was used to reconstruct the conductivity map (Bissessur and Bhurtun, 2005).

SIRT usually produces good quality reconstructions when allowed sufficient iterations, but it can be slow to converge and may require many iterations before an acceptable error tolerance is reached. Hao et al. investigated an adaptation to SIRT and proposed the addition of a pre-conditioning matrix to the C and R matrices that act as the relaxation factor in the update equation (Hao et al., 2013). They show that the convergence rate is improved by adding this pre-conditioning with little loss to reconstruction quality. For details of the derivation of this pre-conditioning matrix see (Hao et al., 2013).

4.3.2.4. Machine learning-based methods. By treating the inversion problem as an unknown function that maps the measurements onto an intensity map, the inversion problem can be solved by approximating this mapping function using an artificial neural network (ANN). The general idea is to train an ANN on measured examples of known conductivity maps, or by using simulated data, and then apply the sensor measurements to the ANN directly as input to produce the normalised conductivity map.

A key factor in this approach is how the conductivity map is represented or parameterised to the ANN. By using a small multi-layer perceptron (MLP) Palka et al. (2009) demonstrated two different approaches to the representation of the conductivity distribution. In the first approach the entire 3D conductivity map is discretised and binarised so that a 0 indicates the background conductivity and 1 indicates the presence of an object. This simplified coding scheme keeps the ANN smaller and easier to train as each discrete element of the conductivity map is represented by a single binary output of the ANN. They also present an alternative parameterised approach whereby the conductivity map is represented by the inclusion function that encodes the location of a potential object that acts as a local disturbance in the conductivity map. The inclusion function is defined on each row (scanline) of the conductivity map and is defined by two parameters, the position of the inclusion (P) and the length of inclusion (L). Both the parameters are defined separately for each scanline in the conductivity map. The collection of parallel scanlines form a 2D plane with each position associated with a parameter pair (P,L). This parameterisation of the conductivity map results in a smaller output from the ANN and therefore simplifies the training and potential performance of the model further but has the disadvantage of only allowing for one distinct inclusion per scanline which limits the kind of conductivity images that can be reconstructed. For details of this comparison between the methods see (Palka et al., 2009). They train their small MLP model by using simulated data and the largest version of their network only had 300 neurons across three layers. Given the small model it is unsurprising that they report unsatisfying results from the first encoding approach. The smaller model that uses parameterised encoding of the conductivity map produced better results, but they also report poor localisation in the direction of the scanline due to the limitation of the parameterisation choice.

A more modern approach that uses larger networks based on proven architectures from the field of deep learning was investigated by Xiao et al. (Xiao et al., 2018). They use simulated data to perform several experiments to compare traditional reconstruction methods like Landweber iteration and LBP to their method based on the deep neural networks. They propose two different network architectures, the first based on a combination of a stacked auto-encoder and three-layer MLP, and the second based on a larger fully connected MLP. The first approach is partially trained in an unsupervised way (the auto-encoder) and the second approach is fully supervised. They train all their models on simulated data with varying amounts of Gaussian noise added. Compared with the traditional Landweber and a direct LBP reconstruction, they report improved reconstruction accuracy from both of their suggested models but do not compare their results to more commonly used advanced methods like SIRT or CG.

A popular approach to using neural networks for this type of image reconstruction come from the observation that iterative methods like Landweber can be shown to theoretically behave in a similar way to convolutional neural networks (CNNs) that are very popular in the related fields of machine vision and image processing. Jin et al. (2017) demonstrated that a reconstruction method based on a fast iterative solver that approximates the solution but suffers from artefacts, can be combined with a CNN to form a fast and accurate reconstruction method. They use a simple filtered and discretised LBP to approximate the conductivity map and then use this result as input to a CNN which has been trained to remove the artefacts from the approximate result.

They base the architecture of their CNN on the U-Net architecture that is commonly used for image segmentation and denoising in the field of image processing (Ronneberger et al., 2015). They use two synthetic and one real dataset for testing purposes and compare with a standard filtered back projection (FBP) method and one regularised using the total variation (TV) method. They demonstrate that in the more realistic dataset that their method outperforms the FBP and TV methods. The CNN approach is also shown to be much faster computationally than the iterative techniques and has the advantage that regularisation is done implicitly and does not have to have it added explicitly. They note that a major limitation of this approach is that the network needs to be retrained when moving between datasets of different dimensions or sub-sampling factors which limits the practical usability of their technique.

5. Electromagnetic tomography applications

EMT has been applied to various purposes from medical applications, with tissue as a low conductivity medium (Ktistis et al., 2005), to structural applications, where, for example conductive structures such as steel reinforcements are embedded in a non-conducting medium such as concrete (Bissessur and Peyton, 2004a; Bissessur and Peyton, 2004b; Bissessur and Bhurtun, 2005), to oil and gas pipelines (Liu et al., 2022).

Among all applications in the Process Engineering arena flow velocity profile measurements have been the most common purpose generally with many applications in molten metal flow specifically, which is a challenging environment. EMT has also successfully been applied for phase distribution analysis. Detection of crack and defects in pipelines and other structures is also a possibility with EMT.

In the sections below, the literature relating to each area of focus will be discussed.

5.1. Flow velocity profile measurement

EMT has been applied for various applications with the most common purpose being flow velocity profile measurement in various multiphase flows. Table 3 summarizes and breaks down these references.

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Slurry transportation in food, mining and dredging industries, mixing, separation and fluidization process in chemical and pharmaceutical industries, and oil, gas, and water transportation in the petroleum industry, all involve multiphase flows. Research on multiphase flow structure and thus development of a practical multiphase flowmeter is of huge importance for boosting energy efficiency and environmental protection (Cui et al., 2022). Obtaining the multiphase flow parameters of such flows, among which the velocity profile plays a key role, is complex as such flows have rapidly evolving phase interfaces and velocity profiles. The velocity profile of multiphase flows shows robust nonlinear and unstable characteristics in comparison with single-phase flows, hence, obtaining a theoretical description is complicated (Gao et al., 2022).

Table 3
Break down of references for EMT applications to flow profile measurements.

EMT applications to flow velocity profile measurements	Simulation studies	(Xiong and Xu, 2000) (Liu et al., 2005) (Wang and Gong, 2006) (Wang et al., 2007) (He and Xu, 2009) (Liu et al., 2012) (Lehtikangas et al., 2016) (Xia et al., 2020) (Arif et al., 2021) (Gao et al., 2022) (Yang et al., 2022)	
	Experimental studies	Single Phase Flow	(Abrolat and Musch, 2017b) (Abrolat and Musch, 2017a) (Lehtikangas and Vauhkonen, 2017) (Ma et al., 2017) (Vauhkonen et al., 2018) (Cui et al., 2022)
		Double Phase Flow	(Wu and Wang, 2009) (Ma et al., 2015) (Cui et al., 2019) (Vauhkonen et al., 2019)
		Multiple Phase Flow	(Zhang et al., 2015) (Mallach et al., 2018)
		Molten Metal studies	(Ma et al., 2005) (Soleimani, 2010) (Terzija et al., 2010) (Terzija et al., 2011a) (Terzija et al., 2011b) (Wondrak et al., 2014)

Up to now research has demonstrated that optical methods such as Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) provide accurate flow velocity profile measurements. However, such optical methods are only applicable to transparent fluids and pipes and flows with lower void fractions. Electrical Tomography (ET) techniques are non-invasive, low cost and provide high temporal resolution but have low spatial resolution and have an ill-posed image reconstruction. Magnetic Resonance Imaging (MRI) have high accuracy of reconstructed images but are large volume and complex structure equipment with high maintenance cost and provide low temporal resolution. Electromagnetic flowmeters (EMF) which measure the average cross-sectional flow velocity are non-intrusive, corrosion resistant and provide highly reliable and accurate measurements for single phase flows, based on the assumption of uniform conductivity distribution. On the other hand, for multiphase flows in which the velocity profile is naturally asymmetric and the conductivity distribution is non-uniform, it is more complex. Lately, the development of Electromagnetic Flow Tomography (EMFT) has been proposed as a non-invasive, low cost and high precision velocity profile measurement technique. It is an extension of the EMF technique by increasing numbers of excitation coils and measurement electrodes and is a common area of research being investigated for this purpose (Cui et al., 2022; Gao et al., 2022).

5.1.1. Single modality EMFT

EMFT which consists of multiple excitation coils and measurement electrodes was proposed as a resolution to the limitation of EMF for flow evaluation in asymmetric conditions such as in multiphase flows. Application of EMT to the measurement of velocity profile of multiphase flows in which the continuous phase is electrically conductive was evaluated and compared to numerical simulations showing it to be an efficient innovative technique for acquiring volumetric flow rate (Wang and Gong, 2006). In another study Wu and Wang demonstrated that EMT can detect the mixed fluid flow pattern of stratified gas-water flow with measurement precision dependent on vertical distance between adjacent electrodes (Wu and Wang, 2009). In 2015 some of the first flow rig tests in the application of EMT to multiphase flow imaging were presented, with a 16 channel EMT system with 8 excitation coils and the remaining 8 coils floating as receivers applied to several fluids with different conductivities, showing the viability of this application. Detailed experimental analysis of the system response towards various fluid measurements was performed and results demonstrate that a non-homogenous flow of gas bubbles in many conductive backgrounds can be imaged using this technique (Ma et al., 2015). A novel sensor configuration was proposed for the measurement of velocity profile of pipe flows in which two parallel rings of field coils (12 coils) enclosed in two magnetic circuits are arranged on the surface of the pipe and in close proximity to the 12 electrodes. The sensor configuration together with a measurement system and reconstruction algorithm presented good functionality for symmetric and asymmetric flow profiles (Abrolat and Musch, 2017a). The system was also later evaluated with 24 field coils and the functionality of the sensor was confirmed with rotationally symmetric and asymmetric flow profiles (Abrolat and Musch, 2017b). An EMFT system was created with four excitation coils and 16 measurement electrodes with the ability of applying both square wave and sinusoidal coil current excitations and also allowing parallel excitations with multiple frequencies. This system was able to demonstrate the ability of delivering dependable velocity field approximations for both axisymmetric and asymmetric single-phase flows (Vauhkonen et al., 2018). Unlike the current common assumption of insignificant influence of conductivity distributions of moving fluids on the induced electromotive force, a lab scale EMFT measurement system was recently designed with 4 excitation coils and 16 measuring electrodes, applied, and validated by numerical simulations and experiments. The results signify the existence of high-conductivity inhomogeneity actually does have substantial impacts on the boundary potentials (Gao et al., 2022).

5.1.2. Dual modality systems

Much more recent research into the application of EMT to flow profile measurement has focused on the advantages of dual modality systems. Such systems are able to combine the capability of two or more techniques and provide the complementary information for better understanding of investigated multi-phase flows.

Contactless Inductive flow tomography (CIFT) measurements were assessed when used simultaneously with EMT gas/liquid distribution measurements in a slab casting mould with submerged entry nozzle (Wondrak et al., 2014). Three-phase flow imaging when both conductive and non-conductive phases are involved is a challenging area of interest which was tackled with a dual modality Electrical Capacitance Tomography (ECT)- EMT unit and proved to be successful in the case of air-background scenarios compared to when water was used as the background (Zhang et al., 2015). An integrated dual-modality ECT and EMT sensor system was initially designed and then measurements were gathered by a custom-built multi-channel impedance measurement system. The results were then validated by numerical simulations and experimental tests showing reliable measurements with acceptable signal-to-noise ratio (Cui et al., 2019). The application of multi-class LS-SVM (Least Squares-Support Vector Machine) for employing the dual-modality fusion between the two tomography modalities, i.e., the ECT and EMT was evaluated using a combination of Computational Fluid Dynamic (CFD) and finite element method (FEM) simulations. Simulation results demonstrate that the fusion technique has the ability to differentiate the measured three phases and acquire the three-phase distributions in various flow regimes (Xia et al., 2020).

Vauhkonen et al. presented successful experimental results of applying a multimodal imaging system using a previously developed EMFT system for velocity field measurements and a commercial ET system for 2-phase volumetric fractions measurements, for the purpose of measuring the volumetric flow rates in laboratory oil-water and solid-water flow loops, showing reliable measurements (Vauhkonen et al., 2019). Recently Arif et al. presented a joint reconstruction approach with the purpose of enhancing the accuracy of dual modality EMFT and ET for flow rate estimations by improved modelling of the unidentified velocity and conductivity fields. The results demonstrate improved accuracy using the joint reconstruction approach (JRA) with a cross-covariance model in comparison to other approaches (Arif et al., 2021).

A novel concept is presented for the non-intrusive measurement of water volumetric flowrate of a multiphase flow in which EMT is combined with electromagnetic velocity tomography and its challenges and potential improvements have been evaluated (Ma et al., 2017).

5.1.3. Data reconstruction for flow measurement applications

Due to the complexity of EMFT reconstruction algorithms, a major part of the research into this application focuses on improving the data reconstruction process to provide better flow velocity profile measurements. Xiong and Xu theoretically analysed the expressions of the magnetic field distribution in a 2D object space by unravelling the forward problem for a specific two component flow (Xiong and Xu, 2000). Later a chord measurement method and a data fusion algorithm were introduced in order to eliminate the random error of data acquisition of multi-electrode inductance flowmeter as a combination of the inductance flowmeter and the electromagnetic tomographic system (Xu et al., 2001). Finite Element Method (FEM) was applied to simulate the sensing field with a novel parallel excitation using flexible circuit strips array demonstrated to be effective (Liu et al., 2005). He and Xu proposed a novel algorithm based on the Modified Nawton-Raphson method for solid-gas flow measurement which presented better suitability for industrial online two-phase measurements due to its enhanced computation cost and reconstruction quality (He and Xu, 2009). Liu et al. initially presented a comparison of Linear Back Projection Landweber iterative and Tikhonov regularization algorithms and then presented an enhanced Landweber iterative method which applies a Tikhonov regularization reconstruction image as the primary iterative value providing better quality and convergence speed. This technique was verified to be effective through simulation reconstruction (Liu et al., 2012). A novel reconstruction method was proposed, based on finite-element-based computational forward model for calculating boundary voltages and a Bayesian network for inverse problems, for estimation of velocity profiles in complicated pipe flows (e.g. near pipe elbows, solid-water flows in inclined pipes, stratified or multiphase flows) to overcome the limitations of the conventional Electromagnetic Flowmeters (Lehtikangas et al., 2016). The impact of additive, possibly correlated, measurement noise and different prior models on the velocity field reconstructions in EMFT have been evaluated using numerical simulations demonstrating that, if the covariance structure of the noise is taken into consideration, even with relatively high level of correlated measurement noise, the reconstruction method presents practicable approximations (Lehtikangas and Vauhkonen, 2017). Recently the forward problem of EMFT has been further investigated through numerical simulations by taking the conductivity distribution into consideration in dealing with fluids with asymmetric and non-uniform conductivity distributions (Cui et al., 2022). Four reconstruction algorithms have more recently been proposed for mapping velocity profiles using EMFT: the linear back projection (LBP); Tikhonov regularization; simultaneous iterative reconstruction technique (SIRT); and Landweber iteration. All of these assist in reducing the reconstruction complication by referring to the sensitivity model of electrical tomography (ET). Simulation results demonstrate the capability of EMFT for approximation of the velocity profile of water-continuous flows, and quantification of local velocities within the sensor section (Yang et al., 2022).

Although the application of EMT to flow profile measurement of some single phase and multiphase flows have been studied as discussed in this section, the application to many other flows remaiun to be discovered. E.g., more complex single phase Newtonian media such as oil-in-water flows; more viscous flows such as corn syrup solutions; single phase non-Newtonian liquids such as pulp fibre, Xanthan gum, or high concentration milk solutions; and various multiphase media such as solid-water-gas or oil-water-gas, all remain to be evaluated. Also, all research to date has focused on lab scale equipment and flows and therefore the complexities of scale-up to pilot plant scale or commercial scale situations remain to be discovered in the future.

5.2. Molten metal production process

In the continuous process of steel casting, in order to ensure product surface quality and cleanliness of steel, factors such as optimum laminar flow patterns and also degree of pouring nozzle “clogging” are crucial factors. Build-up of alumina on the stopper and in the pouring nozzle disturbs the flow profiles in the mould, causing asymmetric flow and inhomogeneous heat transfer within the mould which in turn will result in quality problems. Application of a robust and safe sensor which would provide the ability to visualize the steel flow and detect clogging would be advantageous (Binns et al., 2001). The high temperature and limited access environment of the submerged entry nozzle in industrial steel casters makes the monitoring process challenging. Table 4 shows the references of literature applying EMT to molten metal production processes.

Table 4
References for EMT applications to molten metal production processes.

EMT applications to molten metal production processes	
(Binns et al., 2001)	(Terzija et al., 2010)
(Ma et al., 2005)	(Terzija et al., 2011a)
(Soleimani et al., 2007)	(Terzija et al., 2011b)
(Forbriger et al., 2008)	(Wondrak et al., 2011)
(Soleimani, 2010)	(Chen et al., 2022)

In 2001 Binns et al. (2001), evaluated the possibility of using electromagnetic methods for this application. Some initial results, a summary of the applied image reconstruction process, a discussion of the likely future usage of a tomographic or multi-frequency methodology, reconstruction image procedures and the possibility for flow measurements were presented and the necessity for additional research, especially in some more significant topics in the future, was discovered. Ma et al. (2005) explored the application of EMT for envisaging the molten steel distribution within a submerged entry nozzle and were able to demonstrate great potential for future industrial processes. Ma et al. (2005) presented an electromagnetic tomography system with an eight coil sensor array intentionally designed and built for hot trials. Resulting images reconstructed from both cold sample and hot pilot plant trials demonstrate an acceptable illustration of the fluctuations of real molten steel flow profiles within the submerged entry nozzle, with low frame acquisition rate (1.35 s per frame). The computational aspects of the forward and inverse EMT problem have been evaluated and applied to reconstruct images of a high-contrast conductivity example of steel/argon flow demonstrating the first nonlinear image reconstruction results for EMT (Soleimani et al., 2007). In 2010 Soleimani (2010) presented an EMT system with improved temporal resolution (8 times faster imaging) by using data from one excitation at a time using the Kalman-filtering approach instead of the traditional one frame data of all excitation coils. The improved EMT system was tested on a molten metal flow continuous casting unit. Application of EMT to a number of variations of this challenging situation was later evaluated and its ability in classifying the various flow regimes and identifying individual bubbles in a two phase GaInSn / Argon flow at lab scale was again proven (Terzija et al., 2010). The study was later continued by applying an EMT system with 8 uniformly-spaced inductive coils for observing the behaviour of GalnSn/Argon flow, which has comparable conductive properties as molten steel at room temperature (Terzija et al., 2011a). In a later study the same group of researchers improved the system from 10 kHz to 40 kHz sinusoidal excitation waveform and from 10 to 40 frames per second capture rate (Terzija et al., 2011b). Wondrak et al. (2011) used combined electromagnetic tomography by using Mutual Inductance Tomography (MIT), for visualizing the metal distribution in a submerged entry nozzle, and Contactless Inductive Flow Tomography, for monitoring the flow in the mould, in order to evaluate various flow regimes including pressure and mould level oscillations, transitions between double and single vortex flows, and transient single port ejections. The first report of using EMT for monitoring the process of molten converter slag solidification, during which the copper slag changes from the molten state to solidification state during the cool-down for more than an hour, was recently presented by Chen *et al.* The results were validated using x-ray diffraction and scanning electron microscopy suggesting the feasibility of the EMT-based technique for this purpose at lab scale (Chen et al., 2022). The practicality of Contactless Inductive Flow Tomography (CIFT) as a key factor in real time control of continuous casting of liquid steel at lab scale has been recently further demonstrated, despite the challenge presented for inductive measurements due to electromagnetic actuators. This study demonstrated the possibility of reliable compensation for the effect of the electromagnetic brake on the measurement of the flow induced magnetic field. Full integration of CIFT in a feedback loop of the model predictive controller (MPC) remains to be evaluated (Glavinić et al., 2022).

Research in this section mainly demonstrates EMT as a promising technique for the monitoring of molten metal flow at lab scale and evaluation of this application to larger scale plants remains to be evaluated in the future.

5.3. Phase distribution

Tomography techniques can be applied for the investigation of multiphase flows with different density, conductivity, and permittivity. But for a three-phase gas-liquid-solid flow, it is generally more challenging for the current tomographic tools to visualize the distributions of all three phases and some simplifications such as assuming two disperse phases as one united phase would be required (Cui et al., 2019). The advantages of the EMT technique have been combined with other techniques to provide phase distribution information in a number of more complex multiphase flows and situations.

Cui et al. (2019) provided a dual-modality imaging device by combining electrical capacitance tomography (ECT) and electromagnetic tomography (EMT) for monitoring a gas-liquid-solid flow and visualization of the distribution of all three phases.

Wang et al. combined the advantages of single modality EMT and electrical resistance tomography (ERT) into dual-modality sensors (EMT/ERT) for the purpose of visualizing the distribution of a three-phase medium in a gas-liquid-solid three-phase fluidized bed containing magnetic catalyst. Numerical simulations have been carried out to understand mutual interference with both EMT and ERT and the optimal configuration of the dual modality sensor has been confirmed (Wang et al., 2022b). A new image reconstruction algorithm was also proposed based on Guided Image Filtering (GIF) and image statistics to enhance the fusion of EMT and ERT techniques for the purpose of monitoring cross-sectional three-phase distribution for gas-liquid-solid fluidized bed (Guo et al., 2022).

In order to resolve the complexities due to the ill-conditioned nature of Electromagnetic tomography based on tunnelling magnetoresistance (TMR-EMT) for the purpose of visualizing the solid phase distribution in a gas-liquid-solid three-phase fluidized bed, a novel image reconstruction approach, based on GIF and regularization theory, is proposed to enhance the reconstruction quality (Wang et al., 2022a). A novel approach is also proposed for approximation of the solid fraction in gas-liquid-solid fluidized bed providing more accuracy in which the magnetic field distribution is first extracted, and the correlation between the boundary data and the corresponding permeability of the cross-section is obtained. Then, the effective medium model is applied to approximate the solid fraction of the cross-section based on the corresponding permeability (Liang et al., 2022).

With the rapid technological advancements in all sensing systems, research into multimodality sensing systems will remain a promising area to be evaluated. Combining the advantages of EMT with the advantages of other tomographic or non-tomographic techniques will be able to provide for enhanced applicability of the resulting system to more complex situations.

5.4. Crack / defect detection

Application of EMT, often with the use of inductance coils to produce and detect the magnetic field, for the non-destructive evaluation (NDE) arena and detection of faults and defects in solid objects has been broad. Langley et al. applied a tunnelling magnetic resistor (TMR) to expose a field produced by a drive coil and utilized this data to visualize objects inside shielded enclosures (Langley et al., 2017). A novel reconstruction method is proposed by Wang et al. using EMT based on sparse regularization for the purpose of reconstructing the distribution of defects in a metal object (Wang et al., 2017). Later Mukaiyin et al. were able to prove EMT as a promising technique for examination of metallic pipelines and detection of pipe opening and leakages through a finite element analysis simulation study (Mukaiyin et al., 2019). Recently, a multi-channel EMT system was developed with automatic high-resolution phase measurement and wireless connectivity, which was successfully applied for the detection of a variety of crack sizes on carbon fiber rods (Jeon et al., 2022). Xiao and Ma (2022) were able to produce a reference of skin depth corresponding to the thickness of the tested plate object and a reference frequency range of Eddy Current Testing based on EMT assessing non-ferromagnetic plate materials using finite element simulation.

The ability of EMT in “looking” inside process vessels which are otherwise optically inaccessible, opens the window to the possible use of this technique in detecting many variations from the desired state as long as there are variations in the electric/magnetic fields. These variations or malfunctioning situations may include, but are not limited to, detection of undesired objects, non-homogeneity due to imperfect mixing, fouling build-up, etc., which can be a good area of research in the future.

6. Conclusions and future work

EMT is a novel technique attracting the attention of researchers for a wide range of purposes. It is obtaining continuously increasing acceptance in various industries and thus developing into a more recognised measurement tool for assessment and monitoring of numerous processes including chemical engineering processes. The discussions in this paper show there have been a wide variety of research conducted to date on the advancements of this technique on many aspects and the various applications and measurement purposes it has been successfully applied to in the Chemical/process Engineering arena to the present. Among the various tomography techniques, EMT is one of the newer, less evaluated techniques, so a lot of potential research areas remain to be evaluated. Further advancements into the system hardware, such as sensor and excitation unit design, will enhance the accuracy and reliability of EMT measurements, while improving the data reconstruction techniques will provide for improved information extraction from the obtained data. Combining the advantages of multiple modalities into one unit will also expand the applicability of the resulting unit for various further purposes and situations. Application of EMT to more complex media such as oil-in-water flows, more viscous flows such as corn syrup solutions, single phase non-Newtonian liquids such as pulp fibre, Xanthan gum, or high concentration milk solutions, and various multiphase media such as solid-water-gas or oil-water-gas remain to be evaluated. Larger scale processes such as pilot plants and industrial scale plants are situations yet to be evaluated. Application of EMT for other purposes such as mixing, phase holdup, solid particle suspension or precipitation, phase boundary, Cleaning-in-Place (CIP), and malfunction (e.g., foreign body detection, fouling build-up) investigations remain to be assessed in the future. Applications of EMT to other areas such as Food, Dairy, Pulp and paper and many more processes also remain to be discovered.

Due to the fact that studies to date have been concentrated mainly on lab scale equipment and for research intentions, fostering EMT applications for the purpose of conducting real process monitoring and evaluation of process plants is a major research gap required to be explored in the future. Application of EMT to plant scale monitoring and control needs greater accuracy, better measurement frequency and more robustness. Such features are being improved everyday through research and thus could result in more potential applications of this technique. The global advantage of EMT would be uncovered once it has reached a state to be installed on a plant scale process vessel and can be utilized for the monitoring, detection and investigation of numerous elements and for numerous objectives all together. Furthermore, the final purpose of this area of research would be conducting closed loop process control utilizing EMT measurements.

CRediT authorship contribution statement

Mohadeseh Sharifi: Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Brent Young:** Supervision. **Jaco Fourie:** Writing – original draft. **Bill Heffernan:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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