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A Review on the Developments, Potentials and Challenges of Application of Metal Products and in Metal Industry Using Process Tomography System

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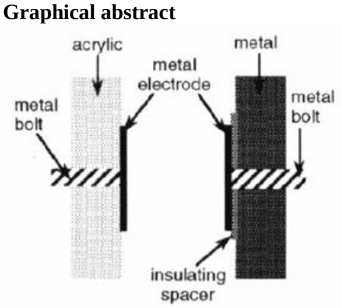
Graphical abstract



Abstract

This paper will provide an overall view of the developments, potentials and challenges of industrial applications involving metal products and in metal industry using process tomography system. The primary focus of the review is to highlight the differences occurred in process tomography in using metallic and non-metallic product especially involving the steel pipes which includes the differences in sensor arrangements (ERT, ECT, EIT), the issues that arises in the use of metal and steel products besides in the metal production itself.

Keywords: Electrical resistance tomography; electrical capacitance tomography; electrical impedance tomography; metal, steel pipes; pipelines; corrosion; erosion; defect; crack; forward and inverse problem; structural health monitoring; nondestructive testing

1.0 INTRODUCTION

Industrial process tomography (IPT) is generally a cross sectional imaging of parameters of industrial processes and usually a function of time [1]. In IPT, the three classifications of sensor systems are transmission mode, reflection mode and emission mode techniques [2] and the four typical tomography section are sensor array, data acquisition system, image reconstruction and display system [3, 4] as shown in Figure 1.

In this paper, the authors hope to highlight the developments, potentials and challenges of industrial applications involving metal products particularly steel products and in metal industry processes using process tomography systems. The primary motivation of this review is the wide use of metal products in industrial applications due to its strength properties at a reasonable cost besides the fact that the use of metal products will always be a dominant contributor in improving the human life as metal could be recycled without reducing the quality of metal itself. However, the focus of this review will emphasize on steel but will also include other metals due to the fact that steel is a very common metal used for industrial applications. In the U.S, the steel industry provides 150, 000 well-paying jobs and is among the most productive, efficient, and technologically sophisticated industries in the world [5]. The successes of this industry could be seen in the new steel grades currently produced which are not able to be made 10 years ago with 55 percent of US steel industry inputs are from scrap.

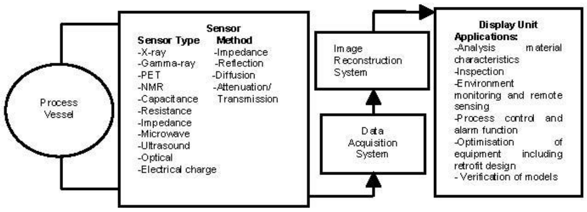


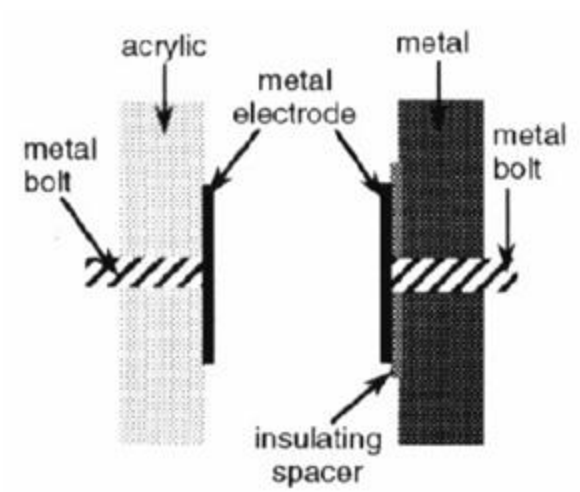
Figure 1 Block diagram of typical tomography system [3, 4]

The sections are divided into 1.0 Introduction, 2.0 Difference in sensor arrangements between metal and non-metal pipe for Electrical Resistance Tomography (ERT), Electrical Capacitance Tomography (ECT), and Electrical Impedance Tomography (EIT) 3.0 Examples of application in fluid properties determination, Structural Health Monitoring (SHM) and Nondestructive Testing (NDT) 4.0 Examples of application of tomography in metal industry particularly the steel industry from upstream to downstream 5.0 Conclusions.

2.0 DIFFERENCE IN SENSOR ARRANGEMENTS

2.1 ERT Sensor Arrangements

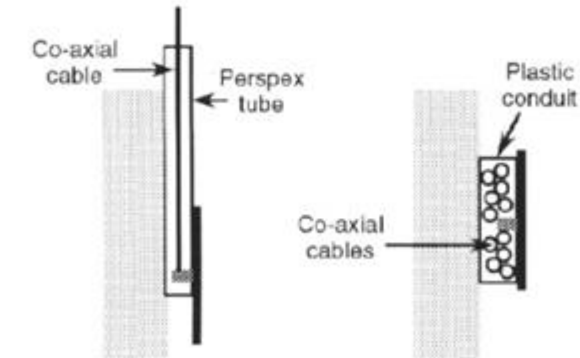
In ERT systems, the sensors must be in continuous electrical contact with the electrolyte inside the process vessel [6] and more conductive than the electrolyte in order to obtain reliable measurements. An important attention needs to be taken on the different way of installing metal electrode on metal pipe and non-conducting pipe considering to the measurement that is taken is the resistance.



(a) (b)

Figure 2 Difference in arrangement between electrode installations to (a) a non-conducting and (b) a conducting pipe [6]

In Figure 2, a commonly non-conducting pipe e.g. acrylic and an electrically conducting metal pipe e.g steel is used to illustrate the arrangement. The primary reason for this arrangement (b) is to eliminate the direct short-circuits contact between two conducting materials, i.e metal electrode and pipe. The spacer should be very much wider and taller than the electrode to mimic a non-conducting walled vessel but usually there will be a trade-off between spacer/electrode dimensions [6]. Besides that, one should consider the length of signal-carrying cable between the electrode and the current injection/voltage measurement circuitry when building the sensors into the vessel. Larger associated stray capacitance and current leakage which causes highly undesirable phase shifted signals could be caused by longer cable. In addition, electromagnetic interference from heavy duty electrical machinery could cause the cable acting like an antenna.



(a) (b)

Figure 3 (a) Retro-fitted via vertical poles and (b) Retro-fitted via a circular conduit [6]

In Figure 3, Dickin [6] has proposed two strategies to be used when drilling holes into the vessel to mount the electrodes is not an option. Figure 3(a) one of a number of hollow poles, each fitted with an electrode, carefully lowered into position from a secured carrier arrangement at the top of the vessel. The poles are held in place by attaching them to the wall using an adhesive or a second 'ring' structure towards the opposite end of the poles. Electrode's cabling to the data acquisition system is done by each of the water-tight hollow plastic tubes. On the other hand, Figure 3(b), one of an array of electrodes is fabricated into a hollow water-tight plastic conduit used to carry the cabling and then attached to the vessel wall via a number of adhesive pads. The disadvantage of the proposed retrofitting strategy is the non-intrusive nature of the measurement procedure is neglected. The authors recommended that 5% of the vessel's diameter (T/20) is the most retrofitted electrodes can protrude without severely affecting the flow patterns. However, the advantages of retrofitting in this manner is the process vessel is unaffected and the plastic tubes or conduit, which act as an insulating backing for the metallic electrodes, can be used in many types of process vessel.

2.2 ECT Sensor Arrangements

Generally, an Electrical Capacitance Tomography (ECT) sensor is a ring of thin rectangular electrodes usually between 8 and 16 of them separated from each other by small gaps around an insulating pipe or vessel, which contains the fluids or materials to be imaged as shown in Figure 4 [7]. An additional grounded metallic pipe surrounded the assembly acts as an electric screen. The electrodes are commonly placed on an electrically non-conducting (i.e non-metallic) tube but has a limitation of unable to contain a high-pressure flow. An example of solution to the said limitation is as shown in Figure 5. In the design, there is an inner borosilicate glass tube through which the fluids flow, with the electrodes placed on its exterior surface, surrounded by an outer stainless steel pipe, equipped with hermetic electrical connectors.

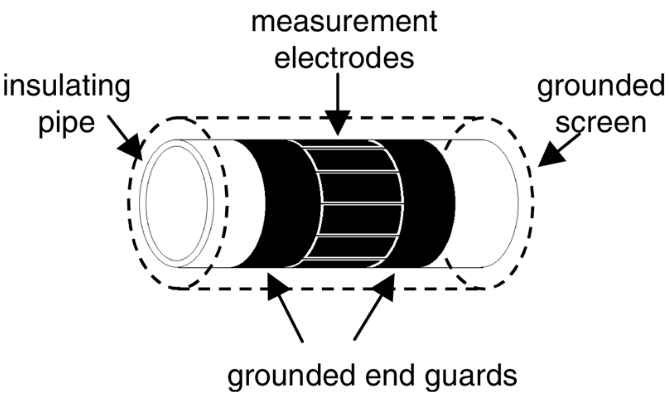


Figure 4 Basic structure of a typical ECT sensor [7]

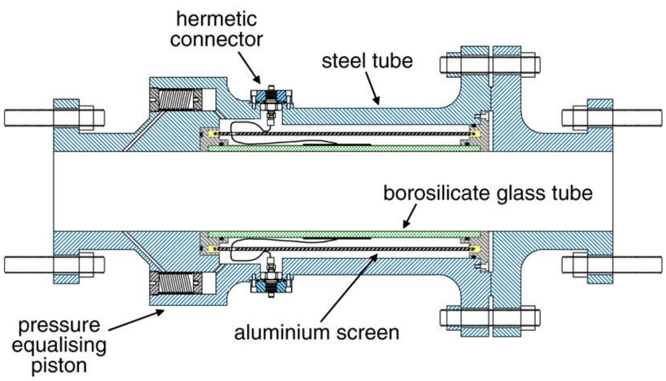
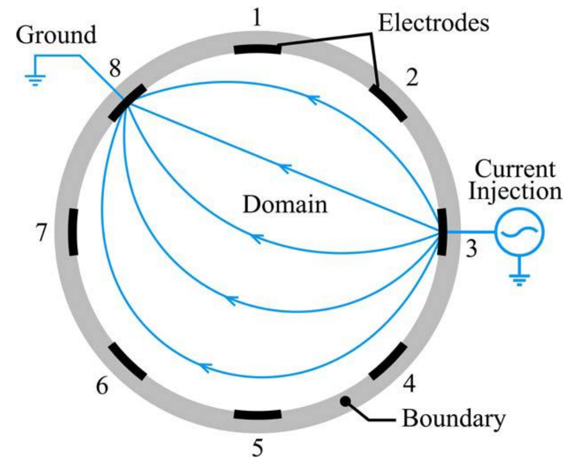


Figure 5 Schematic diagram of sensor [7]

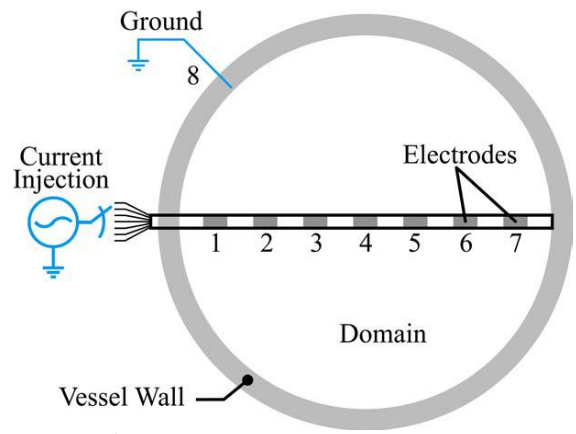
2.3 EIT Sensor Arrangements

In 2002, Liter [8] has carry out the Benchtop Validation Test to show that the EIT system would provide accurate results using the wall as ground, a simple verification experiment was conducted to provide a one-dimensional (vertical) step-variation in electrical conductivity, resulting in two electrically differentiable regions as shown in Figure 6. In his experiment setup, the electrode rod used is fabricated from a PVC tube with a 2.2 cm outer diameter and a 1.5 cm inner diameter. The author uses two sets of electrodes with each consisted of 7 ring electrodes, one set made from 0.04 mm thick copper foil and the other from 0.07 mm thick stainless steel 304 foils. Other dimensions are all the same. The length of the electrodes is 2.54 cm and is wrapped around the rod with a 3.5cm edge to edge separation between them. The distance between the bottom electrode and the base of the standpipe is 7.0 cm when the rod is inserted into the standpipe. The liquid level h_l is kept at 7.0cm above the top electrode to maintain vertical symmetry. Electrode ground wires are attached to the vessel exterior. The particle bed consists of polystyrene spheres of diameter d_p = 3 mm, allowed to fall through the water into random packing. Subsequently, the particles are stirred to remove trapped air bubbles, and then the particle-bed surface is planed flat.

A metal cylinder known as standpipe of diameter d = 14.7 cm with an electrically insulating base is used as the vessel (ground electrode) [8]. The electrode rod is positioned coaxially inside the standpipe. The standpipe is filled to various heights h_b with solid particles and a liquid (water with a small amount of aqueous sodium nitrate to control the liquid conductivity), resulting in a region of lower conductivity in the saturated particle bed, and a region of higher conductivity in the liquid above the bed.



Schematic of an EIT System Applied to an Electrically Insulating (Non-conducting) Vessel [8]



Schematic of an EIT System Applied to an Electrically Conducting Vessel [8]

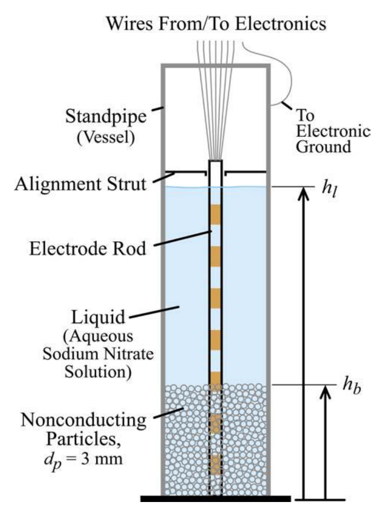


Figure 6 Schematic of verification experiment consisting of an electrode rod inserted coaxially in an electrically conducting standpipe filled with non-conducting solid polystyrene particles and liquid [8]

3.0 APPLICATION IN FLUID PROPERTIES DETERMINATION, SHM AND NDT

Tomography technology helps to reduce the two most important concerns in the industry i.e harm to humans and the environment. Media corrosion, cavitation erosion, welding defects cracking, stress corrosion cracking and materials deterioration causes leakage and explosion accidents after a certain period of time [9]. Besides that, an issue due to corrosions or defects in the pipelines and storage tanks could cause the oil and gas as well as petrochemical company heavy financial lost annually in product losses, production downtime, environmental cleanup efforts and fines [10]. The National Society of Corrosion Engineers estimates a maximum of 25% costs reduction by implementing best practices and updated with new technologies.

In ultrasonic tomography, the implementation of steel pipes faced an unique issue which is irrelevant to other types of pipes of acrylic, PVC and plastics material [11], [12], [13]. Steel pipes have high attenuation of ultrasonic energy and the high influence of bulk waves besides the worst internal reflections within enclosed pipes [14]. In order have a good understanding of the limitation of steel pipe, one need to first understand the fundamental physical properties of waves. The ultrasound are commonly tested in two modes i.e Longitudinal and Shear waves [15], [16] although there are other modes which includes shear waves, surface waves and in thin material as plate waves[17].

Abbaszadeh [11], [12], [13] used transmission-mode technique as the sensing mode in which only longitudinal mode of ultrasonic wave propagation is desired to determine the fluid properties in a steel pipe. COMSOL, a Finite Element Simulation software was used to determine the optimum frequency of the ultrasonic sensor and to determine the receiving time of the longitudinal waves and Lamb waves. The wave's properties differ by using steel pipe as the Lamb Wave reaches the receiver at the opposite side of transmitter before the longitudinal wave where as for other material used, the longitudinal will arrived first and the first data received could be assumed to be from the longitudinal wave. In his proposed method, there is a trade-off in selecting the optimum frequency. An increase in frequency causes an increase in pressure level of the Lamb Wave and capability improvement to diagnose small particles [14], [18] but a decrease in pressure level of the longitudinal wave [11], [12], [13]. Based on the parameters, Abbaszadeh have chosen in his experiment, the optimum frequency is found to be 40 kHz.

Ironically, Lamb waves are used as guided ultrasonic waves to locate and size flaws in metal pipe e.g aluminum pipe [19]. In the study of corrosions, defects, or commonly known as Structural Health Monitoring (SHM) and Nondestructive Testing (NDT), one will find hard to exclude the guided acoustic waves. History of possibility of providing spatially localized information with guided waves through the combination of multiple transmission measurements and tomographic techniques started in the early 1990s by Hutchins's group [20]. The research trend on guided wave tomography is mainly on flat plate geometries with fewer works on pipe applications [21]. When the pipe wall thickness is small compared to its radius (5% to 10%), guided wave tomography can be implemented by ideally unwrapping the section of pipe between the arrays and treating it as a flat plate. The ring arrays are therefore transformed into two parallel linear arrays and the guided wave tomography problem reduces to the classical borehole tomography configuration [22].

The authors have observed in the research on crack and corrosion of steel pipe using various type of tomography, there are three main focuses. The first group of researchers focuses on the physical properties of the pipe which includes flexible pipe e.g the development of X-ray computed tomography (CT) systems for on-site inspection of flexible pipelines with special consideration for the end fitting area on topsides [23], pipelines e.g. infrared tomography performed for four types of stainless steel and carbon steel pipes [9], material composition of high temperature pressure the steel pipe e.g X-ray microtomograhy used in three dimensions quantification of collinear cracks from a low-carbon gas pipeline X65 steel colony [24], pitting corrosion of stainless steel with high resolution in situ X-ray microtomography in three dimensions. [25], at welding point e.g ultrasonic and radiography for weld integrity [26], a 2-coils Magnetic Induction planar sensor of transmitter and receiver coil [27], inspection of multi-hole steel floral pipes using a low frequency longitudinal guided wave mode [28], aged pipes e.g X-ray Radiography for transfer pipes for the low-level radioactive liquid waste are made of steel or stainless steel [29]. The second group has carried out experiments on different condition in which the steel pipe is in which includes in underground pipes e.g a subsurface radar system for imaging buried pipes [30] and concrete-filled steel pipes e.g application of Electromagnetic Acoustic Transducers (EMATs) transmitting and receiving cylindrical guided waves [31]. Finally, the third group researches on the technique itself which includes ultrasonic waves based imaging technique using longitudinal ultrasonic waves for detecting defects in pipeline structures [32], a numerical simulation analysis of pipeline corrosion using Electrical Capacitance Tomography (ECT) [33]

Considering the number of research in the area of Structural Health Monitoring (SHM) and Nondestructive Testing (NDT) is tremendous, only selected research will be discussed here. An aspect of guided wave tomography is the helical modes. Willey [34] have introduced a general inversion method to extract information in the higher-order helical modes. Based on the observation for a given transmit–receive transducer pair, there exists infinite helical wave paths that connect the transmitter to the receiver each corresponding to a different number of turns around the pipe. Larger number of turns around the pipe due to the higher order of the helical path causes better ray coverage in the circumferential direction.

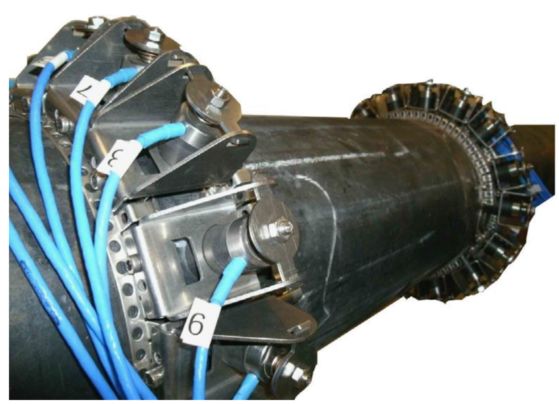


Figure 7 An 8″ diameter pipe is instrumented with two ring arrays each containing 16 EMAT transducers [34]

4.0 APPLICATION IN METAL INDUSTRY

In the manufacturing or production line, besides challenges in applying tomography system using end product of metal product in the production of other products as explain previously, there is also significant concern in the metal production itself particularly in metal casing process. An example of this is an electromagnetic approach for tomographically visualizing the molten steel distribution within a submerged entry nozzle (SEN) [35]. The system consists of an eight-coil sensor array, data acquisition unit, associated conditioning circuitry, and a PC computer, which was designed and constructed for hot trials. The tomography helps to ensure an optimum laminar flow pattern in the casting mold and stable meniscus [36].

Ultrasonic testing is also used to detect defect inside billets [37] which includes pulse echo method and transmission method. In pulse echo method, pulse wave is launched into the billet from a transducer and received at the same transducer. The received signal includes the back scattering wave from a defect when the defect exists on the path. Ultrasonic wave attenuated by diffusion and scattering in steel [38] which cause the pulse echo method not suitable to be used for high-attenuation billets due to echo from the defect becomes small. Some of the important facts include the longer the distance between the transducer and the defect, the larger the scattering attenuation coefficient, the lower the echo levels. On the other hand, the transmission method, uses ultrasonic computerized tomography (CT) using time of flight (TOF) of longitudinal wave [37]. Some of the advantages on the transmission method with CT include (1) the distance between the transmitter and the defect is large, the received signal level by the transmission method was higher than by the pulse echo method; (2) due to TOF is derived from pulse compression of the received signals, the effect of noise can be reduced; and (3) the receivers can be arranged widely against the incidence angle of the signal, the measurement points can be increased, and the defect information can be extracted easily by reconstruction. As a result, the transmission method with CT is predicted to be more robust in measurement for high-attenuation billet than the pulse echo method.

In high-quality steel making, one of the important factor is nonmetallic inclusions which is the degree of steel cleanness [39]. Generally, Computed X-ray tomography (XCT) detects and measures inhomogeneities giving an absorption contrast in volumes. The detection of inhomogeneities such as shrinkage pores, microfocus x-rays computed tomography (μXCT) is not a new technology. Ferum-based materials are usually noisy, of poor contrast and the interpretation is affected by measurement artefacts which caused the evaluation of CT-data more difficult. Due to the higher x-ray absorption coefficient of the base metal, the said inhomogeneities and non-metallic inclusions are more difficult to detect in continuously cast steel slabs. High-resolution μXCT and synchrotron tomography (sXCT) was used to obtain measurements of non-metallic inclusions and pores in steel slabs. These inhomogeneities can be differentiated clearly via the grey value only with monochromatic synchrotron radiation. A sufficient difference in the x-ray absorption coefficient for quantifying these particles as well as pores of over critical size reliably with XCT-techniques is provided by the mass density of oxidic and sulphuric inclusions is about half the density of iron [40]. Destructive Metallographic Methods is used to distinguish between the different kinds of inhomogeneities while target preparation determines its exact position.

Besides the upstream metal industry, we would like to include some of the applications of tomography system in the middle and downstream metal industry. A brief elaboration Magnetic Induction Tomography (MIT) or also known as Mutual Inductance Tomography or Eddy-Current Tomography [41] will be done to assist readers to grasp a good understanding. In a typical Magnetic Induction Tomography, coils are used as transmitters and receivers. A changing magnetic flux is set up by establishing a sinusoidal current in the transmitting coil which induces a voltage across the terminals of the receiving coil. The induced signal picked up by the sensing coil is proportional to local magnetic field strength B, which is referred to as the "background" or "primary" signal, and represented as a phasor [42], [43].An eddy current will be induced on an object if the object is positioned between two coils which causes a magnetic field perturbation Δ B in B. The detected signal on the receiving coil can be expressed as a fraction Δ B / B of the primary field. In the detection of metallic objects ($\sigma > 10^6$ S/m) placed between two coils, the primary effect is a reduction in the amplitude of magnetic field strength B, i.e Δ B is real and negative, resulting from surface currents on the object [42]. In Wei's experiment [41] to verify the metal-sensing capability using MIT system, he has chosen two aluminum sheets of 0.5 mm thickness and 2mm thickness and a steel sheet of 1 mm thickness. All other dimensions of all the three sheets are 112 mm x 214 mm). The findings from his work are as follows: (i) metallic objects do cause a real negative perturbation signal at the receiver and the signal change is more significant when the metal sheet is closer to either the transmitter or the receiver with the receiver being slightly more sensitive; (ii) The shapes of the patterns were very similar for all three metal sheets. (iii) The larger difference in permeability between aluminium and steel have no significant effect on the magnitude change. (iv) Small electromagnetic penetration into both metal sheets. W. Yin [44] has explained that the reason (iv) discussed is the reason behind low-frequency systems is used high-conductivity materials as low-frequency systems can have sensitivity to subsurface structures due to the high skin depth.

Besides for production purposes, tomography is also used in the protection of environment even for the steel industry. "Orphan" radioactive sources could be melted with scrap metal in the upstream industry [45]. Muon tomography could be used to identify unobserved radiation scanning portals high density material of lead for instance by the scattering of muons inside materials to build a three-dimensional density map of a volume. Fine-tuning optimization is needed in case of tight time constraints and large analysed volumes because the scan of the portal has to be performed with a minimal impact on the queuing schedules of the facility hosting the portal even it is most effective when a large number of muons is gathered.

5.0 CONCLUSIONS

As a summary, there are still much improvement needs to be done in various areas in implementing tomography system in metal (steel) products and the industries that manufacture them.
The properties of steel pipes that makes it special compared to other type of pipe material is that steel pipes have high attenuation of ultrasonic energy, the high influence of bulk waves and the worst internal reflections within enclosed pipes. From the authors' observation, the current method used for ECT, ERT and EIT are generally intrusive in nature. Various application of tomography in metal industries in the upstream such as scrap properties determination and metal casting besides the midstream and downstream such as sheets processing could be observed. It is hoped that some of the examples of different arrangements using different type of sensors between metallic and non-metallic pipes and the elaboration of application of

tomography in various stages of metal industry would be beneficial to readers.

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