INDUSTRIAL SINGLE PHOTON EMISSION COMPUTED TOMOGRAPHY (ISPECT) SYSTEM FOR OIL-WATER TWO-PHASE FLOW IN A HORIZONTAL PIPELINE

HANAFI BIN ITHNIN

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Universiti Tun Hussein Onn Malaysia

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Dedicated to my beloved family, especially my parents, Ithnin Kasim, Siti Halijah Tahir, Faridah Abu Bakar, Mohd Lip Rahman and Rohaya Omar, my dearest wife Norliana Mohd Lip, and beloved daughter Nur Fatihah Hanafi. Also, my supportive supervisor Assoc. Prof. Ts. Dr. Elmy Johana Mohamad and co-supervisor Ts. Dr. Nazrul Hizam Yusoff.

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ABSTRACT

Understanding the oil-water flow pattern throughout the transportation in a horizontal pipeline would ensure it is efficiently supervised and could greatly assist in managing it. Hence, the flow pattern data can be utilised to design and create better process equipment such as for the oil-water separator. A nonagonal industrial single photon emission computed tomography system (iSPECT) imager for horizontal pipeline monitoring system is constructed and presented in this thesis. The iSPECT system can visualise the oil-water interface level inside a horizontal pipe. The goal of this study is to use the iSPECT system as an instrument to inspect and monitor the flow pattern of the oil-water separation process in the industry. Previous works on industrial iSPECT were focused on imaging the radiotracer distribution in vertically installed equipment, such as mixing tanks. However, this work investigates the capability of using 36 Sodium Iodide detectors by simulating different detectors arrangements using MCNPX code to image the flow pattern inside a horizontal pipe. The nonagonal ring arrangement was found to be the best detection geometry from the simulation study. Subsequently, the nonagonal iSPECT hardware and software for data acquisition and image reconstruction were fabricated and tested in a static condition. Technetium (Tc-99m) mixed with water was used as radiotracer material, providing the gamma-ray emission within the flow. Three experiments were done, where the Tc-99m radiotracer was left stationary inside the pipe, the flowing tracer in water flow and the flowing tracer in oil-water flows. The images (visualisations) of dynamics flow for water-only flow and liquid-liquid (oil-water) flow were obtained, and all images were then analysed. The visualisation results show the system is able to image water levels up to 60% of the region diameter with an error of ±5%. The information obtained undeniably would be able to help in the equipment designing and verification of existing computational modelling and simulation techniques. Finally, it would ensure process control and monitoring during the oil-water separation process is proficiently administered and monitored.

ABSTRAK

Memahami corak aliran minyak-air dalam saluran paip mendatar akan memastikan ia diselia dan diselenggara dengan cekap. Oleh itu, data corak aliran boleh digunakan untuk mereka bentuk dan mencipta peralatan proses yang lebih baik seperti untuk pengasingan minyak-air. Pengimej sistem tomografi berkomputer pancaran foton tunggal industri (iSPECT) nongonal untuk sistem pemantauan saluran paip mendatar dibina dan dibentangkan dalam tesis ini. Sistem iSPECT boleh menggambarkan paras antara fasa minyak-air di dalam paip mendatar. Matlamat kajian ini adalah untuk menggunakan sistem iSPECT sebagai instrumen untuk memeriksa dan memantau corak aliran proses pengasingan minyak-air dalam industri. Kerja-kerja terdahulu berkaitan iSPECT tertumpu pada pengimejan pengedaran penjejak radioaktif dalam peralatan yang dipasang secara menegak, seperti tangki pencampur. Walau bagaimanapun, kerja ini menyiasat keupayaan menggunakan 36 pengesan Natrium Iodida dengan mensimulasikan susunan pengesan yang berbeza menggunakan kod MCNPX untuk pengimejan corak aliran di dalam paip mendatar. Susunan bebentuk nonagonal didapati sebagai geometri pengesanan terbaik daripada kajian simulasi. Selepas itu, perkakasan dan perisian iSPECT nonagonal untuk pemerolehan data dan pembinaan semula imej telah direka dan diuji. Technetium (Tc-99m) dicampur dengan air digunakan sebagai bahan penjejak radioaktif, memberikan pancaran sinar gamma dalam aliran. Tiga eksperimen telah dijalankan, di mana pengesan radio Tc-99m dibiarkan pegun di dalam paip, pengesan yang mengalir dalam aliran air dan pengesan yang mengalir dalam aliran air minyak. Imej (visualisasi) aliran dinamik untuk aliran air sahaja dan aliran minyak-air diperoleh, dan semua imej kemudiannya dianalisis. Hasil visualisasi menunjukkan sistem ini dapat imej paras air sehingga 60% daripada diameter paip dengan ralat ±5%. Maklumat yang diperolehi akan dapat membantu dalam reka bentuk peralatan serta sebagai pengesahan kepada teknik pemodelan dan simulasi sedia ada. Akhir sekali, ia akan memastikan kawalan dan pemantauan semasa proses pengasingan minyak-air ditadbir dan dipantau dengan lebih cekap.

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LIST OF ABBREVIATIONS

CARPT	-	Computer Assisted Radioactive Particle Tracking
CT	-	Computed Tomography
ECT	-	Electrical capacitance tomography
EIT	-	Electrical Impedance Tomography
ERT	-	Electrical Resistance Tomography
FBP	-	Filter Back Projection
FWHM	-	Full Width at Half Maximum
iSPECT	-	Industrial SPECT
MCNPX	-	Monte Carlo N-Particle eXtended
MIT	-	Magnetic Induced Tomography
ML-EM	-	Maximum Likelihood Expectation Maximization
MPI	-	Massage Passing Interface
MRT	-	Mean Residence Time
NORM	-	Natural Occuring Radioactive Material
PET	-	Positron Emission Tomography
PEPT	-	Positron Emission Particle Tracking
PMT	-	Photo Multiplier Tube
PRSF	-	Point Source Respond Function
ROI	-	Region of Interest
RPT	-	Radioactive Particle Tracking
RTD	-	Rasidence Time Distribution
SCA	-	Single Channel Analyser
SPECT	-	Single Photon Emission Computed Tomography
UT	-	Ultrasonic Tomography
WMS	-	Wire Mesh Sensor
XCT	-	X-ray Computed Tomography

LIST OF SYMBOLS

α	-	Alfa particle
γ	-	Gamma-ray
n	-	Neutron particle
K	-	Collimator hole constant
R_c	-	Collimator resolution
D	-	Diameter of interest region
d	-	Collimator aperture width
l	-	Collimator hole depth
b	-	Point source-collimator distance
p	-	Projection
f	-	Line intergeral function
h_{ij}	-	Mean value of permittivity distribution
λ_j	-	Tracer concentration
Y_i	-	Detector measurement of incoming radiation
Re	-	Reynolds number
ρ	-	Fluid density
U_s	-	Fluid velocity
μ	-	Fluid viscosity

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CHAPTER 1

INTRODUCTION

1.1 An Overview of Computed Tomography

The first patented computed tomographic instrumentation was developed by Sir Godfrey N. Hounsfield using an x-ray machine in the early 1970s (Petrik, *et al.,* 2006). Since then, the development of a computed tomography system, especially for medical purposes, has been rapid due to its ability to image human internal organs non-invasively. It has to be emphasised that the ability to image an object non-invasively means tomography systems are not constrained to the medical field only. Eventually, more variation of the tomography system has been developed varying in the different sensor design, imaging speed, image reconstruction algorithms, and cost limitation. The tomographic system used for industrial purposes started evolving in the 1980s. The term process tomography is used to describe the usage of tomography systems to image industrial process flow.

In general, there are two types of tomography, namely soft-field and hard-field tomography. Soft-field tomography depends on the medium's physical properties interaction to be imaged with the sensor. Examples of soft-field tomography are electrical capacitance tomography (ECT), electrical resistance tomography (ERT), and electrical impedance tomography (EIT) (Beck, *et al.*, 1997; Borcea, 2002; Dickin & Wang, 1996). On the other hand, hard-field tomography disregards the interaction with the medium properties and only measures the source trajectory and attenuation of the source. The hard-field tomography system examples are X-ray micro-tomography

(XCT), Ultrasound tomography (UT), and gamma-ray tomography system (Wang, Yu, & De Man, 2008; Ozanyan, Wright, Stringer, & Miles, 2011; Johansen, 2005).

Gamma-ray computed tomography system can be operated in two modalities: transmission and emission. In transmission modality, a gamma-ray source emits the photon to penetrate the object of interest and attenuate within the body of different densities with varying attenuation (Hsieh, 2003). The attenuated gamma rays are detected by an array of detectors placed opposite the gamma source. This measuring process is repeated with multiple angles of projections. From these projections, the image reconstruction process is applied to produce the interesting object's tomographic image. Examples of gamma-ray transmission tomography systems are gamma process tomography (TECDOC, 2008) and GammaSpider (Abdullah, *et al.*, 2015).

On the other hand, in the gamma-ray emission tomography modality, a gamma-ray source known as the radioactive tracer is injected into the interest object or process and then distributed in the object depending on the flow of the process study. The distributed tracer inside the object emits gamma rays and subsequently is detected by the arrays of sensors surrounding the object. The image reconstruction process is applied to map the tracer distribution from these multiple arrays of projection. Examples of emission tomography systems are single-photon emission computed tomography, SPECT and positron emission tomography, PET (Wernick & Aarsvold, 2004). Chapter two presents a detailed discussion of these two modalities of gamma-ray tomography. This research will focus on the emission modality of the gamma-ray tomographic system in industrial applications. From here, the term SPECT refers to the medical use of emission tomography, while the term iSPECT refers to the industrial application of emission tomography. The similarities and differences of these two systems will be discussed in detail in Chapter 2.

1.2 Research Background

Process tomography is a system used to image the industrial process's cross-sectional parameters in relation to space and time. In contrast with other computed tomography systems, a process tomography system needs to have a high temporal resolution. This system's measurement can provide an important description of flow parameters such as flow pattern, flow composition, flow distribution, and more. More importantly, process tomography system measures can provide these parameters without the need to interrupt the flow process (Beck & Williams, 2012). This information is essential in optimising and designing industrial processes and process equipment, thus improving the accuracy of industrial flow process measurements in general.

Nowadays, several types of process tomography systems are being developed from soft-field and hard-field systems. Examples of developing process tomography systems are Electric Capacitance Tomography (ECT), Electric Resistant Tomography (ERT), Optical transmission tomography, Gamma-ray tomography, and X-ray tomography (Beck, et al., 1997; Borcea, 2002; Dickin & Wang, 1996; Wang, Yu, & De Man, 2008; Ozanyan, Wright, Stringer, & Miles, 2011; Johansen, 2005). Each of these different tomography systems has different measurement principles, and developing a suitable system depends on the interested application. The applicability of electrical tomography systems such as ECT and ERT depends on the process flow's electrical properties. On the other hand, density differences in the flow process are needed for measurement using an X-ray tomography system. The next consideration in developing the process tomography system is the suitability of the sensor to be installed in the flow process. The different sensor needs different preparation, such as special wall material. It is also important to acknowledge that the flow process needs to be compatible with the measurement principle and not be blinded. Other considerations are the tomography system's temporal and spatial resolution in the interest of the flow process to be imaged.

The process tomography system developed in this study is considered for the application of the tomographic image of a liquid-liquid flow pattern. An example of liquid-liquid flow is oil-water flow. The flow pattern is how fluids move through a reactor. Density gradients, caused by temperature or composition variations, tend to control the fluid's overall flow pattern. Liquid-liquid two-phase flow systems such as oil-water are used in many industrial applications. Examples of their applications in the petroleum industry include emulsions preparation, oil-water mixture separation, and transportation. Accurate prediction of liquid-liquid flow characteristics, such as flow pattern transition, is important in many engineering applications such as process optimization, equipment design, safety and reliability, product quality and yield, and trouble shooting (Yusoff, 2012). For example, understanding and predicting flow pattern transitions in process optimization help engineers in identify the most efficient operating conditions, equipment sizing, and process configurations. This optimization leads to improved process performance, reduced energy consumption, and enhanced product quality. On the other hand, different flow patterns have distinct characteristics, such as liquid holdup, droplet size distribution, and interfacial area, which directly affect mass and heat transfer rates, pressure drop, and the behavior of process fluids. Failing to accurately predict flow patterns can result in operational instabilities, equipment damage, and safety hazards (Al-Safran *et al.,* 2020). Despite its importance, the liquid-liquid flow has not been explored to the same extent as the gas-liquid flow. The density difference between the two phases is relatively small, while the viscosity ratio encountered can extend over several orders of magnitude, both of which bring great complexity. Thus, this study will serve as a new tool for imaging the stratified oil-water flow inside a horizontal pipeline.

1.3 Problem Statement

Imaging a liquid-liquid flow such as oil-water flow gives essential information for the design of industrial process flow systems, process flow optimisation, and process flow monitoring. The ability to control and monitor oil-water flow is crucial to the industry such as oil and gas industry. Oil-water separation is an important process in the oil and gas industry. Currently, a new method has been proposed for the oil-water separation process through pipeline transfer. However, monitoring such separation process remains a problem as the measurement of the separation process needs to be non-intrusive and compatible with the robust industrial environment. The radiotracer method has been a proven method in process flow measurement for the oil and gas industry. Although the current radiotracer measurement method only provides one-dimensional information. An advanced measurement technique is needed to enable the industry to image the flow pattern inside an opaque pipe. Therefore, this study aims to develop an industrial SPECT system for imaging the radiotracer distribution in an oil-water flow system that is able to image different oil-water percentages. Thus, the information gathered can help engineers develop better equipment for oil-water separation.

1.4 Research Objectives

The main objectives of this study are:

i. To optimise the detection geometry of an industrial SPECT imaging device for oil-water pipeline imaging.
ii. To design and fabricate the iSPECT hardware and the image reconstruction and analysis software for the iSPECT system.
iii. To investigate the ability of the iSPECT system to image the oil-water stratified flow in a horizontal pipeline system.

1.5 Research Scope and Limitation

This study covers the optimisation, design and fabrication of an iSPECT system which will finally be applied to image an oil-water flow. Thus, several parameters must be contained in this study's research scope. The scope of this study will cover the development of an industrial SPECT system for a pipeline which will provide a 2D image for oil-water flow studies covering software and hardware development. For the hardware sensor system, the limitation of this study is that it only uses 36 numbers of one-inch sodium iodide NaI detectors with lead collimators. A maximum number of 36 detectors was used in this study because the size of the region to be imaged is 20 cm in diameter. Thus, for a one-inch collimated detector, the calculation for the geometrical spacing in relation to the full width at half maximum at the centre of the interest region indicates 36 detectors are sufficient to image a 20 cm circular region (detail calculation can be referred to in Table 4.3).

Next, the iSPECT system's model was built in the simulation study, and gamma-ray detection calculations were executed using Monte Carlo N-Particle eXtended,

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APPENDIX A

LIST OF PUBLICATION AND AWARDS

Publications

1. Ithnin, H., Mohamad, E.J., Lip, N.M., Yusoff, N.H. (2022). Industrial SPECT System for Imaging Water Level Inside a Horizontal Pipe. In: Wahab, N.A., Mohamed, Z. (eds) Control, Instrumentation and Mechatronics: Theory and Practice. Lecture Notes in Electrical Engineering, vol 921, (pp. 310-320). Springer, Singapore

2. Ithnin, H., Mohamad, E. J., Lip, N. M., Mustapha, I., & Hizam, N. (2022). Industrial SPECT simulation for imaging radiotracer distribution in a pipeline using MCNPX code. Sci. Technol. Res. Tech. Bull, 15, 10-15.

3. Ithnin, H., Mohamad, E. J., Lip, N. M., & Yusoff, N. H. (2021). MCNPX Modelling and Simulation of Point-source Detection using Different iSPECT Geometrical Arrangement. ELEKTRIKA-Journal of Electrical Engineering, 20(2-3), 103-106.

4. Ithnin, H., Mohamad, E. J., Yusoff, N. H., & Lip, N. M. (2020, September). An Experimental Gamma-ray Emission Computed Tomography System for Intensity Mapping of An Isotropic Sealed Source. In 2020 IEEE Student Conference on Research and Development (SCOReD) (pp. 306-309). IEEE.

5. Ithnin, H., Mohamad, E. J., Yusoff, N. H., Hassan, H., & Lip, N. M. (2020, April). Development of industrial single photon emission computed tomography (ISPECT). In "I*OP Conference Series: Materials Science and Engineering*" (Vol. 785, No. 1, p. 012024). IOP Publishing.

6. Ithnin, H., Mohamad, E. J., Yusoff, N. H., Hassan, H., & Lip, N. M. (2018). Study on influence of different gamma-ray energy on images of an industrial CT system, "*International Journal of Integrated Engineering*," 10(4), p. 102-104.

Award

1. Gold Medal "*Software and Simulation for iSPECT System*" at The International Research and Symposium and Exposition (RISE) 2022. Universiti Tun Hussein Onn Malaysia (UTHM). Virtual Platform.