UNIVERSITI PUTRA MALAYSIA

HYDRODYNAMICS BEHAVIOR IN QUADRILATERAL BUBBLE COLUMN USING INDUSTRIAL RADIOTRACER TECHNIQUES

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By

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Radiotracer technique is well established assisting tools for troubleshooting and process optimization in process industries. Industrial radiotracer has proved to be a very useful tool to examine and improve the design of pilot-scale systems. However, to date, no detailed large-scale studies have been performed to investigate the capability of nanoparticle radiotracers in any pilot plant or laboratory scale vessels. Thus, the performances of the nanoparticle radiotracer for industrial application purposes are being questioned. This study has demonstrated the entire design development process of a bubble column reactor test rig for investigating hydrodynamics behaviour using industrial radiotracer techniques with aid of complete system. The influence of superficial gas velocity and sparger design on gas hold up in bubble column has been successfully studied. Therefore, the hydrodynamic parameters of the bubble column reactor are validated using the conventional method with the aid of high-speed camera technology. The results indicate that the higher sparger opening area contributed to higher gas holdup up to 50% from initial water level and increased the value superficial gas velocity which resulting increasing Reynolds number value. From the qualitative observation analysis and Reynolds number information, the flow regimes for bubble column reactor are determined from homogeneous to heterogeneous flow successfully. The solid nano-sized particle radiotracer $^{198}Au@SiO_2$ has been synthezised and characterized for tracing liquid phase effectively. The performance of newly synthesized industrial radiotracers was successfully validated by investigating aqueous phase system in bubble column reactor at different air flow rates and sparger design using radiotracer flow measurement method and residence time distribution studies with accuracy more than 98%. The results of flow measurement show that the experimental volumetric flow rate is in good agreement with conventional flow meter value. Moreover, residence time distribution results indicate that the bubble column reactor was fit with perfect mixers in series with exchange model (PMSE) from the RTD mathematical simulation. Both techniques have validated the synthesized industrial nanoparticle radiotracer $^{198}Au@SiO_2$ performance in tracing liquid phase effectively as a comparison with conventional radiotracer ^{99m}Tc. Whereas, the study has managed to measure and simulate particle calibration map and verify position reconstruction algorithm for radioactive particle tracking technique using MCNPX code. The method was successfully applied to model the motion and simulated spiral trajectory of the single particle radioactive tracer ^{198}Au and ^{46}Sc. The simulation results have successfully reconstructed 26,000 tracer particle histories map to be used for particle tracking in bubble column reactor. The radioactive particle tracking facility and encapsulated tracer particle has been designed and developed. The hydrodynamic behaviour investigation in bubble column reactor is carried out using simple radioactive particle tracking experiments. Finally, by introducing alternative non-destructive, non-invasive, and effective radioisotope techniques for understanding hydrodynamics behaviour of multiphase systems, it offers a high potential for the niche of industrial applications towards future commercialization of process diagnostics and troubleshooting services in Malaysia.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Kejuruteraan

SIFAT HIDRODINAMIK DALAM LAJUR GELEMBUNG BERSISI EMPAT MENGGUNAKAN TEKNIK PENYURIH RADIOAKTIF INDUSTRI

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Teknik penyurih radioaktif merupakan alat bantuan yang telah berjaya dibangunkan bagi penyelesaian masalah dan pengoptimuman proses di dalam industri pemprosesan. Penyurih radioaktif industri telah terbukti menjadi salah satu alat yang amat berguna bagi memeriksa dan memperbaiki reka bentuk sistem skala perintis. Namun, sehingga hari ini, tiada kajian berskala besar telah dilaksanakan bagi mengkaji kebolehupayaan penyurih radioaktif nanopartikel di mana-mana loji perintis atau reaktor berskala makmal. Oleh itu, prestasi sebenar penyurih radioaktif nanopartikel untuk aplikasi industri sedang dipersoalkan. Kajian ini telah menunjukkan keseluruhan proses pembangunan reka bentuk pelantar ujian reaktor lajur gelembung untuk mengkaji tingkah laku hidrodinamik menggunakan teknik penyurih radioaktif industri dengan bantuan sistem yang lengkap. Kesan kelajuan superfisial gas dan rekabentuk plat berlubang terhadap gas pegangan di dalam lajur gelembung telah berjaya di kaji. Justeru itu, parameter hidrodinamik reaktor lajur gelembung telah disahkan menggunakan kaedah konvensional dengan bantuan teknologi kamera berkejaluan tinggi. Keputusan menunjukkan bahawa luas bukaan plat berlubang yang tinggi menyumbang kepada kenaikan gas pegangan sehingga 50% daripada aras air yang awal dan meningkatkan nilai kelajuan superfisial gas yang menghasilkan peningkatan terhadap nilai nombor Reynolds. Daripada analisa pemerhatian kualitatif dan maklumat nombor Reynolds, rejim aliran berjaya ditentukan dari aliran homogen kepada heterogen. Sintesis dan pencirian penyurih partikel pepejal bersaiz nano $^{198}Au@SiO_2$ telah dilakukan bagi mengesan fasa cecair dengan lebih efektif. Prestasi penyurih radioaktif industri yang disintesis baru ini telah berjaya disahkan dengan mengkaji sistem fasa akueus dalam reaktor lajur gelembung pada kadar aliran udara dan rekabentuk plat berlubang yang berbeza menggunakan kaedah pengiraan aliran penyurih radioaktif dan kajian taburan masa mastatutin dengan

ketepatan lebih daripada 98%. Keputusan bagi pengiraan aliran menunjukkan bahawa kadar alir volumetrik eksperimen mempunyai padanan yang baik dengan nilai meter aliran konvensional. Tambahan pula, keputusan simulasi matematik taburan masa mastautin menunjukkan bahawa reaktor lajur gelembung adalah berpadanan dengan model tangki sempurna sesiri tertukar (PMSE). Kedua-dua teknik telah mengesahkan prestasi penyurih radioaktif industri nanopartikel $^{198}Au@SiO_2$ lebih efektif dalam mengesan fasa cecair sebagai perbandingan dengan penyurih radioaktif konvensional ^{99m}Tc. Sementara itu, kajian ini juga berupaya untuk mengukur dan simulasi peta kalibrasi partikel dan mengesahkan kedudukan algoritma pembinaan semula bagi teknik penjejakan partikel radioaktif menggunakan kod MCNPX. Kaedah ini berjaya dilaksanakan bagi pemodelan gerakan dan mensimulasikan trajektori lingkaran untuk partikel penyurih radioaktif tunggal ^{198}Au dan ^{46}Sc. Keputusan simulasi telah berjaya membina semula 26,000 koordinat pemetaan sejarah partikel penyurih untuk tujuan penjejakan partikel dalam reaktor lajur gelembung. Fasiliti penjejakan partikel radioaktif dan enkapsulasi partikel penyurih telah direkabentuk dan dibangunkan manakala penyelidikan sifat hidrodinamik dalam reaktor lajur gelembung telah dijalankan dengan menggunakan eksperimen penjejakan partikel radioaktif yang ringkas. Akhir sekali, dengan memperkenalkan teknik alternatif penyurih radioaktif yang efektif, tidak memusnah dan tidak invasif bagi memahami sifat hidrodinamik sistem pelbagai fasa, ia menawarkan potensi yang tinggi kearah pengkomersilan perkhidmatan diagnostik proses dan penyelesaian masalah dalam bidang aplikasi perindustrian di Malaysia pada masa hadapan.

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LIST OF ABBREVIATIONS

ADM	Axial dispersed plug flow model
ADME	Axial dispersed plug flow with exchange model
BSS	International Basic Safety Standards
CCTII	Centre for Computed Tomography and Industrial Imaging
CFBS	Circulating fluidized bed system
CLR	Continuous leaching reactor
CLSM	Confocal laser scanning microscopy
CNC	Computer numerical control
CREL	Chemical Reaction Engineering Laboratory
CSTR	Continuously stirred tank reactor
CT	Computed tomography
DAS	Data acquisition system
DHDT	Diesel hydro treater
DS	Dial setting
EDXRF	Energy dispersive X-ray fluorescence
FCCU	Fluid catalytic cracking unit
FEED	Front-end engineering design
FWHM	Full width of half-maximum
HCT	Hydrocarbon transport
HPGe	Hyper pure germanium
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LANL	Los Alamos National Laboratory
LLD	Lower-level discriminator
MADS	Mesh adaptive direct search
MCA	Multichannel analyzer
MCNPX	Monte Carlo N-Particle Extended
MOSTI	Ministry of Science, Technology and Innovation
MRT	Mean residence time
$Na_3C_6H_5O$	Tri-sodium citrate
NAA	Neutron activation analysis
NaI	Sodium iodide
OSL	Stimulated luminescence dosimeter
PBR	Photo bioreactors
PBT	Pitched blade turbine
PC	Personal computer
PMP	Perfect mixers in parallel model
PMR	Perfect mixers with recycle model
PMS	Perfect mixers in series model

PMSE	Perfect mixers in series with exchange model
PMT	Photomultiplier tubes
PPE	Personal protective equipment
PVC	Polyvinyl chloride
RPT	Radioactive particle tracking
RR	Rotary rack
RTD	Residence time distribution
SCA	Single channel analyzer
SS	Stainless steel
SSE	Sum of the squares of the errors
TBR	Trickle bed reactor
TDPP	Technology demonstration pilot plant
TEM	Transmission electron microscopy
TEOS	Tetraethyl orthosilicate
TIFF	Tagged image file format
ULD	Upper-level discriminator
UV-VIS	Ultraviolet-visible spectroscopy

CHAPTER 1

INTRODUCTION

1.1 Introduction

An advantage of multiphase flow system plays an important contribution to the chemical and petrochemical industry. Operating systems involving multiphase processes are common in this discipline from the processing of power sources and chemicals for the production of goods, sustenance and advanced materials. Despite the wide usage of two or more system phases, the approach embraced for their design is generally by instinct and dependable guidelines instead of on first principles. The primary explanation behind this condition of issues is that the internal flow structure is greatly unpredictable and the connection between the micro and macro-scale are not completely established. Therefore, comprehensive understanding of the quite a few process hydrodynamic issues and problems experienced with multiphase systems remains incomplete. The lack of comprehensive technical and hydrodynamic details at the micro-scale and the mathematical challenges correlated with the methods for operating the randomness of the multiphase conditions are the major justifications behind the failure to treat these defects absolutely from a theoretical basis.

The effective methodology towards the understanding of such complicated flows requires dependable information, which thus relies on upon the usage of modern measuring procedures equipped for non-intrusive investigation and also the capacity to produce the required data over the absolute flow field. Furthermore, it is preferable that such techniques are susceptible for automation to minimize human involvement in the data acquisition process. Progress development in designing and modelling the transport properties in multiphase system reactors depends on the availability of such experimental tools where can produce and construct the information for model validation. In this condition, researchers usually end up with investigations that will give important data about flow mapping. This data is very important in order to construct new models for determination of flow rate, residence time distribution, mean residence time, and radioactive particle tracking techniques dynamics characterization, and so on. This information will be used at least to build up an ideal framework plan and system design optimizations.

Industrial process engineers and researchers have been aware about the benefits of nuclear radiation techniques for detection and evaluating process performance non-invasively. For instance, transmission and penetration of gamma rays will not damage the physical and chemical interference along the process and enable large non-transparent systems for evaluations. The utilization of gamma emitter radioactive tracers known as radiotracers empowers the inspections of various structures and dynamic characteristics in multiphase reactors. Generally, characteristics such as residence time distributions and circulation appropriations, and homogenization and mixing of phases of gases, liquids and/or solids can be measured by using appropriate tracer techniques.

Industrial radiotracer technology is a measurement tool for troubleshooting and problem solving to plant malfunctions and to maintain the optimum plant condition using radioactive techniques. Recently, radiotracer technology used for flow rate measurement, flowmeter calibration, residence time measurement, and mean residence time determination. The most challenging radioactive based techniques which not available and have not yet introduced in Malaysia is radioactive particle tracking technique. Radioactive particle tracking techniques consist of arranging scintillation detectors externally placed beside multiphase reactors to measure the emitted gamma radiation. To extrapolate flow information from a specific component in the homogeneous and heterogeneous system, the particle was marked as a tracker by radioisotope tracers can be adapt into the process to label the media as a single radioactive particle. Nevertheless, use of a single unique radioactive particle, resemble a tracked phase, results in information that is more accurate and position sensitive, and the adequacy and adaptability of measurements with one single radiotracer particle exceed the potential outcomes offered by the conventional technique with labelled multi-particle injections. After accurate information of the flow pattern of the tracer successfully measured, it can figure out a wealth of transient and steady-state information. The instantaneous and local Lagrangian flowrate and velocity can be obtained by time-differentiation of the tracer positions, and additional information using Eulerian and Lagrangian reference frames.

The chemical form is also very important to make the tracer stay with the material stream all the time otherwise it will be separated from the fluid. With huge particles, it was very hard for the tracers to mix homogeneously with water/oil under certain condition. Thus, unique single radioactive particle is produced from the selected radioisotope, which embedded and sealed accordingly to the specified density, size and shape to the phase to be tracked. The single solid radioactive particle acts as a marker of the phase whose velocity field to be mapped. The advanced radioactive particle will guarantee the safety of radioisotope from dispersed into the environment and induce contamination.

The main purpose of this research is to design, develop and implement advanced industrial radiotracers for investigating process characteristics and understanding the complex hydrodynamics behaviour of multiphase systems in the quadrilateral multiphase flow bubble column with four side/edges and four vertices polygonal column structure. The innovatively designed quadrilateral bubble column reactor test rig will be advantages in ease of operation, low operating and maintenance cost that can be adapted to specific configurations according to practical requirements. Quadrilateral bubble column reactor will provide the achievements for intimating contact between a dispersed gas, continuous liquid and fluidized solid phase. Different types of sparger plates will provide unique distribution profiles variety due to different holes area percentages.

The experiments will cover in multiphase condition (gas–liquid phase) at ambient temperature plus recirculation of liquid phase with the help of controllable gaseous flow to implement measurement techniques. This uptake experiments will comprise the evaluation of hydrodynamic parameters in bubble column reactor using the conventional method with the aid of high-speed camera technology. Thus, the knowledge contributes to dynamics behaviour and parameters information has been obtained earlier for better understanding in transport phenomena in the systems before further evaluation using industrial radiotracer technology can be executed. The expectation of improvement is this unique non-invasive radioisotope technique for investigating process hydrodynamics in multiphase systems will be adapted to its environment in chemical process industries. Thus, improvement in efficiency and stability of gas-liquid phase distributions in quadrilateral bubble column system can be achieved. Consequently, successful completion of these development will allow efficient utilization of the bubble column reactor with better design criteria, improve reactor system efficiency, and ensure a design that leads to stabilize and optimize reactor behavior when scaling up to bigger diameter reactors as well as increasing more confidence among chemical engineers to perform nuclear-based techniques for process optimization and troubleshooting in industries.

1.2 Problem Statement

As it has already been emphasized earlier, refinery and petrochemical industries would be the biggest beneficiary of industrial radiotracer technology. However, the problem will occur when the environment of these industries is not friendly to some radiotracers because of very high temperature and pressure in the plants (IAEA, 2003). Current radiotracers commercially available in the industry was reported not stable with that environment. Until today, there has been no suitable candidate as a radiotracer for high temperature and high pressure where the possibility to decompose or evaporate is high (Goswami *et al.,* 2016). The synthesized radioactive material was required to be tested and verified before applied to the process industries. To date, no detailed large-scale studies have been performed to investigate the capability of nanoparticle radioactive in any pilot plant or laboratory scale vessels. Thus, the performances of the nanoparticle radiotracer for industrial purposes are being questioned. In this study, the specific experiment will be designed to verify and validate the use of nanoparticle radiotracer in tracing fluid flow in bubble column system.

Radiological safety is the primary concern when performing any radiation-based experiments which using unsealed radioactive source known as a radiotracer. Thus, the radiation safety of each technique and safety of radioactive materials need to be prioritized by allowing only competent radiation workers who are registered with the regulatory board to perform all the preparation and measurements. To date, Malaysian TRIGA PUSPATI nuclear research reactor does not allow the neutron activation for the liquid form samples to prevent any unpredictable radioisotopes leakage inside the reactor core. Thus, nanoparticles radiotracer in the form of solids must be prepared and it will be much easier to disperse and dilute the radiotracer into the desired solution in future. Meanwhile, the experimental setup will be the next concern to perform any measurement and investigations without involving radiation contamination, leakage and complexity to assemble and re-assemble set-up in minimizing radiation exposure during experimental works. This concern will be included when making the decision to design, develop and fabricate multiphase flow test rig.

Therefore, new facilities, new radioactive material, and complete scientific verification are required concerning the effects of each parameter on the process optimization results. Research questions had been set up such as what are the best reactors to study gas-liquid phase system and how can radiotracer be prepared and utilized for investigating multiphase system in process industries? What are the characterizations of hydrodynamics behaviour in quadrilateral bubble columns can be investigated using industrial radiotracer techniques? How was the performance of the newly developed nanoparticle radiotracer compared to conventional radiotracer?

1.3 Research Significance

The quadrilateral bubble column reactor was developed for better understanding of fluid dynamics in multiphase chemical reactors in process industries using radioactive material in a safe manner. The main benefit of designing and fabricating quadrilateral bubble column reactor is to provide a new alternative method to investigating industrial radiotracer technology compared to the current conventional problem-solving methods in oil, gas, and energy sector. This strategic research is in line with the national key economic area (NKEA) to sustain the integrity of facilities and maintain the optimum condition at downstream area of the sector and to promote commercialization by introducing new chemical reactor facilities and troubleshooting techniques in

Malaysian Nuclear Agency. Additionally, strategic plan also aims to propagate research activities and international collaboration on technical cooperation projects. The ideas are coming from the proposed project titled advance nuclear radioisotope techniques to study hydrodynamics process in multiphase systems by International Atomic Energy Agency (IAEA). The quadrilateral bubble column is required and significantly important to conduct a numerical study of the hydrodynamic behaviour of the solid-gas-liquid system in validating the advance radioactive particle tracking techniques as a new tool for industrial vessel troubleshooting and problem-solving.

The development of this multiphase reactor will involve designing and fabricating design tools of the quadrilateral bubble column with different types of sparger plates, scintillation detector, calibration holder, column holder frame, mechanical structure for preventive measurements in safety aspects, with different types of gas supplies. The wealth of the project will be the leading platform for Malaysian Nuclear Agency to initiate the advance radioisotope techniques and application to be used in Malaysian oil and gas industries as well as future global nuclear power industries since the correlations studies are similar between slurry bubble columns reactor and 4^{th} generation of smart nuclear power reactor.

Radiotracer technology is a unique tool in many cases for extracting valuable information about industrial processes, thereby contributing significantly to improving and optimizing their performance. Development of the gold nanoparticle applications require the nanoparticles to be chemically stable, uniform in size, and well-dispersed in liquid media for multiphase investigation system in chemical and petrochemical industries. Thus, the gold nanoparticle radiotracers product were purposely developed for radiotracer experiments such as flow rate measurement, residence time distribution, and radioactive particle tracking for understanding hydrodynamics behaviour in the multiphase reactor. In addition, the information obtained from the radiotracer experiments by the radioisotope application also can benefit as alternative process optimization tools in industries.

The following are the direct and indirect output from the study that will contribute to the advancement of industrial radiotracer technology. First, the synthesize nanoparticle radiotracer can be used in high temperature and high-pressure environment and for tracing substance in different phases by modifying its surface structure which having either hydrophilic or hydrophobic properties. Second, the flow measurement using radiotracer can validate and calibrate conventional flow meter and the system residence time and mean residence time information can be obtained for process optimization and troubleshooting. Then, the quadrilateral bubble column reactor was developed to promote gas-liquid phase and the results can be used to verify and validate the performances of the radiotracer. Moreover, the development of radioactive particle calibration data using reconstruction algorithm output will help to tracing the real particle velocimetry of the system non-invasively. Lastly, the output of the study will verify the performance of industrial radiotracer and quadrilateral bubble column reactor as an alternative method to study hydrodynamics behaviour in the opaque system.

1.4 Research Objectives

The main objective of this study is to validate the performance of newly synthesized and fabricated industrial radiotracer as an alternative method for further investigation the hydrodynamic behaviour and process optimization in quadrilateral bubble column reactor. This objective will be accomplished through the following specific objectives:

i. The first objective is to design and develop quadrilateral bubble column test rig with different types of sparger plates for gas-liquid phase investigations using conventional method.

ii. The second objective is to synthesize, characterize, and evaluate the performance of industrial radiotracers ^{198}Au for investigating aqueous phase system in bubble column reactor using radiotracer techniques.

iii. The third objective is to develop encapsulated radioactive particle, measure particle calibration map and verify position reconstruction algorithm using MCNPX code for investigating hydrodynamic behaviour in bubble column reactor using radioactive particle tracking technique.

1.5 Scope and Limitations

The scope of the present study is to design, develop and fabricate quadrilateral bubble column test rig, advanced radioactive particle tracking facility, and synthesis, characterize and evaluate the performance of industrial radiotracers. The study was conducted at the Open Lab, Plant Assessment Technology facility in Malaysian Nuclear Agency due to radiological safety reasons where radioactive contamination is considered. All the testing and repetitive measurement were conducted and executed only by registered radiation workers with Atomic Energy Licensing Board. The neutron activation analysis for radioactive materials only prepared inside the reactor TRIGA PUSPATI (RTP) premises. The radioactive materials used in this study limited to ^{198}Au, ^{46}Sc, and ^{99m}Tc because of their ideal characteristics of short half-life and low energy in order to prevent any radiological effects to the radiation workers. It also needs to be highlighted here that the study is limited to the innovative design quadrilateral bubble column reactor with 6 different types of sparger plate area used because of the limited budget and radiological safety concerns.

The measurement limited to gas feed flow rate only up to 100 L/min as the maximum specification of flowmeter ranged from 20 – 100 L/min.

1.6 Thesis Outline

The thesis divided into 6 research chapters. First chapters covered an introduction to an alternative process for hydrodynamics behaviour investigations in quadrilateral bubble column reactor using radiotracer techniques. This chapter also presents the problem statement, research significance, research objectives, scope and limitations, and thesis outline. Chapter 2 is a concise literature review on industrial radiotracer technology for process optimizations in chemical and petrochemical industry, including a summary of radioisotopes uses and applications of radiotracer techniques that studied before. The experimental design of radiotracer technology and radiation detection technology referring to previous work until the recent work of radiotracer techniques also discussed in this chapter.

Chapter 3 presents the designing and verifying development process using front-end engineering design (FEED) concept development process of bubble column reactor. The comparison of new concept design with other conceptual design is discussed in this chapter. This chapter also focuses on investigating bubble sizes, gas hold-up and bubble rise velocity in quadrilateral bubble column reactor using conventional method with the aid of high-speed camera technology. The results obtained from these hydrodynamic investigations are reported in this chapter.

Chapter 4 described the method used to synthesize and characterize the radioactive gold-silica core-shell structured nanoparticles. The further characterizations methodology of gold-silica nanoparticles using transmission electron microscopy (TEM), energy dispersive X-ray fluorescence (EDXRF), scanning electron microscopes (SEM), ultraviolet-visible spectroscopy (UV-Vis), and neutron activation analysis (NAA) results were also described. This study also validated the performance of nanoparticles radiotracer for tracing aqueous phase and calibrated the conventional flow meter. This chapter also describes the use of industrial radiotracer for investigating residence time distribution of the bubble column reactor systems at different conditions. The results of mean residence time also calculated and discussed here. In this study, the residence time result will be treated before simulation and verification using RTD mathematical model software can be used to extract the optimal parameters of the system.

Chapter 5 describes the methodology used for single radioactive particle tracer preparation and quantification using radioisotope ^{198}Au and ^{46}Sc for tracking hydrodynamics behaviour of solid phase or liquid phase in multiphase reactors.

In addition, the experimental results on tomogram images using X-ray micro-computed tomography and neutron activation analysis results were discussed in this chapter. The reconstruction of calibration map using MCNPX code for radioactive particle tracking techniques. This study will verify the reconstruction algorithm for mapping counts into the particle position coordinates for quadrilateral bubble column reactor. This chapter includes the validation of performance of the fabricated single radioactive particle by implementing simple radioactive particle tracking experiments with specific data acquisition system hardware and software.

The conclusion of the entire work is summarized in Chapter 6 with a brief explanation on the contribution of the study and recommendations for the future works are presented in this chapter.

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BIODATA OF STUDENT

MOHD AMIRUL SYAFIQ MOHD YUNOS was born at Batu Pahat, Johor, Malaysia on October 26th, 1986. He received his primary education at Sek. Rendah Tunku Mahmood (1) – Kluang, Johor. His secondary education was at Sek. Men. Keb. Jalan Batu Pahat – Kluang, Johor. He completed his Matriculation studies in Physical Science at Kolej Matrikulasi Pahang – Gambang, Pahang. In July 2005, he then continued his higher education at Universiti Putra Malaysia (UPM), Serdang and obtained his Bachelor of Science (Hons.) in Materials Science (2008). In May 2009, he continued his education in Materials Science as a Master of Science postgraduate student at the Department of Physics, Faculty of Science, Universiti Putra Malaysia. In the same university, he was pursuing Doctor of Engineering (D.Eng) in Material Science and Engineering at Department of Chemical Engineering and Environment, Faculty of Engineering start from February 2012. Since October 2009, he has been employed as a government research officer by the Ministry of Science, Technology, and Innovation Malaysia. His current affiliation is the Plant Assessment Technology Group, Industrial Technology Division, Malaysian Nuclear Agency. His main area of interest is structural and electrical characterizations of materials, radiation protection, nuclear applications in industry, industrial radiotracer technology, nucleonic gauges applications, computed tomography, and radioactive nanoparticles. He contributed several papers/articles at seminar/conference/exhibition during his doctorate's studies. He has been awarded multiple medal award by participating local and international innovation competition exhibition during his candidature in Universiti Putra Malaysia.

LIST OF PUBLICATIONS

Mohd Amirul Syafiq Mohd Yunos, Siti Aslina Hussain, Jaafar Abdullah, Engku Mohd Fahmi Engku Chik, Noraishah Othman, Shahidan Radiman, *Development of Gold Nanoparticle Radiotracers for Investigating Multiphase System in Process Industries*, **Advanced Materials Research,** 545 (2012) 105 – 110. Published.

Mohd Amirul Syafiq Mohd Yunos, Siti Aslina Hussain, Hamdan Mohamed Yusoff, Jaafar Abdullah, *Preparation and quantification of radioactive particles for tracking hydrodynamic behaviour in multiphase reactors*, **Applied Radiation and Isotopes,** 91 (2014) 57 – 61. Published.

Mohd Amirul Syafiq Mohd Yunos, Siti Aslina Hussain, Hamdan Mohamed Yusoff, Jaafar Abdullah, *Industrial Radiotracer Technology for Process Optimizations in Chemical Industries-A Review*, **Pertanika Journal of Scholarly Research Reviews,** 2 (2016) 20 – 46. Published.

Mohd Amirul Syafiq Mohd Yunos, Siti Aslina Hussain, Hamdan Mohamed Yusoff, Susan Sipaun, *Design and Fabrication of Quadrilateral Bubble Column Test Rig for Multiphase Flow Investigations*, **Scholars Journal of Engineering and Technology,** 5 (2017) 34 – 43. Published.

Mohd Amirul Syafiq Mohd Yunos, Nur Khairunnisa Abd Halim, Siti Aslina Hussain, Hamdan Mohamed Yusoff, Susan Sipaun, *Investigations of Bubble Size, Gas Hold-Up, and Bubble Rise Velocity in Quadrilateral Bubble Column Using High-Speed Camera*, **American Journal of Engineering, Technology and Society,** 4 (2017) 5 – 15. Published.

Mohd Amirul Syafiq Mohd Yunos, Mark Dennis Anak Usang, Hanafi Ithnin, Siti Aslina Hussain, Hamdan Mohamed Yusoff, Susan Sipaun, *Reconstruction Algorithm of Calibration Map for RPT Techniques in Quadrilateral Bubble Column Reactor Using MCNPX Code,* **European Journal of Engineering Research and Science,** 3 (2018) 20 – 27. Published.

Mohd Amirul Syafiq Mohd Yunos, Siti Aslina Hussain, Susan Sipaun, *Industrial Radiotracer Application in Flow Rate Measurement and Flowmeter Calibration Using ^{99m}Tc and ^{198}Au Nanoparticles Radioisotope*, **Applied Radiation and Isotopes,** 143 (2019) 24 – 28. Published.

LIST OF AWARDS

1. **Consolation Prize**, National Nanotechnology Research Innovation Project Competition (PIN`18) Technology Park Malaysia – for project on 'Development of Industrial Gold Nanoparticle Radioactive Tracer for the Early Detection of Problematic Flow Systems in Chemical and Petrochemical Processing Industry'.

2. **Budding Scientist Award 2017**, Nuclear Malaysia Innovation Day Competition 2017, Kajang– for projects on 'Radioactive Particle Tracking Facility'.

3. **Silver Medal Award**, Nuclear Malaysia Innovation Day Competition 2017, Kajang – for 'Radioactive Particle Tracking: Advance Non-Invasive Radiation Based Techniques for 3D Hydrodynamic Visualization in Opaque Multiphase System'.

4. **Bronze Medal Award**, 43rd International Exhibition of Inventions of Geneva 2015, Switzerland – for projects on 'GOLDNANOTRACER'.

5. **Gold Medal Award**, 5th Exposition on Islamic Innovation 2014 (i-Inova2014), USIM – for projects on 'GOLDNANOTRACER - Unique Tracer for Industrial Applications'.

6. **Gold Medal Award**, Malaysia Technology Expo (MTE 2012), Kuala Lumpur – for 'GOLDNANOTRACER – Novel Nanoparticles $^{198}Au@SiO_2$ for Innovative Use In Industrial Process Investigation Using Radiotracer Technology'.

7. **Bronze Medal Award**, Malaysia Nuclear Agency Invention and Innovation Competition, Kajang – for 'Gold Nano Tacer – Novel Nanoparticles $^{198}Au@SiO_2$'.

PATENT APPLICATION

Patent Application No: **PI2014702548**

Title: **A Radioactive Silica-Coated Gold Nanoparticle and A Method for Producing Thereof**

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