

**UNIVERSITY OF GHANA
COLLEGE OF BASIC AND APPLIED SCIENCES**

**EXPERIMENTAL RESIDENCE TIME DISTRIBUTION (RTD) STUDIES ON
EFFECTS OF AXIAL AND RADIAL FLOW IMPELLERS ON
HYDRODYNAMIC PARAMETERS OF STIRRED VESSELS**

By

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Kumasi), 2009**

**A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN
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JULY, 2016.

DECLARATION

This is to certify that this thesis is the result of research work undertaken by **Francis Yaw Acquaye** towards the Degree of M.Phil. Nuclear Technology Applications in Petroleum and Mining Industries in the Department of Nuclear Engineering, School of Nuclear and Allied Sciences (SNAS), University of Ghana, Legon, under the supervision of **Dr. C.P.K Dagadu** and **Dr. K. A. Danso**.

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this University or elsewhere. Duly other works and/or researches done by other researchers cited in this work have been acknowledged under references.

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DEDICATION

This research is dedicated to my parents for their unfailing love, support and prayers throughout the course of this thesis.



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First and foremost, I would like to thank Almighty God, the creator and the controller of the entire Universe for his guidance and protection towards my family and me.

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LIST OF ABBREVIATIONS

RTD	Residence Time Distribution
MRT	Mean Residence Time
CSTR	Continuously Stirred Tank Reactors
GHACEM	Ghana Cement
IAEA	International Atomic Energy Commission
PFR	Plug Flow Reactor
PM	Perfect Mixer
ADM	Axial Dispersion Model
PMS	Perfect Mixers in Series
PMSE	Perfect mixers in series with exchange
PMSB	Perfect Mixers in Series with Back-mixing
PVC	Polyvinyl Chloride
NDT	Non Destructive Testing
CRT	Cumulative Residence Time

LIST OF SYMBOLS AND CONSTANTS

t	Time
$C(t)$	concentration of tracer at time t
δ	Dirac function
u	step injection time
$E(t)$	Normalised data function
C_{bkg}	Background radiation counts
$C(t)$	Activity at time "t"
C_0	Activity at time zero
t	time elapsed (same units as half life)
$t_{1/2}$	half life
C_{exp}	experimental count rate
$C(t_i)$	corrected count rate
λ	Decay constant
\bar{t}	experimental mean residence time
τ	theoretical mean residence time
V	Tank volume
Q	volumetric flow rate
f_d	fraction of dead space

V_{eff} effective volume of reactor

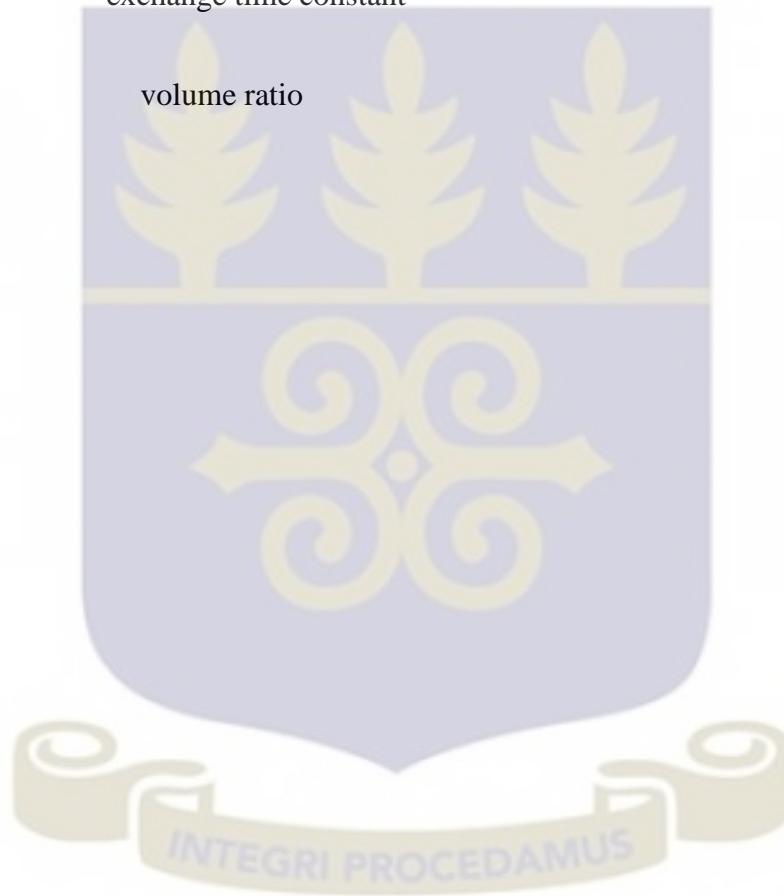
J number of mixing cells

α back flow rate ratio

t_{act} MRT of active volume

t_m exchange time constant

K volume ratio



ABSTRACT

In many industrial and biotechnological processes, stirring is achieved by rotating an impeller in a vessel containing a fluid (stirred tank). Many operations depend to a great extent on the effective mixing of fluids. In stirred vessels, this is achieved by the use of impellers. The vessel is usually a cylindrical tank equipped with an axial or radial impeller which does the actual stirring/ mixing. However, perfect mixing cannot be achieved due to certain malfunctions such as insufficient or excessive mixing, stagnant regions, bypassing and recycling etc. in the vessel. Industries are mostly confronted with the challenge of which flow impeller to use to achieve better mixing. Information on hydrodynamics such as mixing efficiency, Mean Residence Time (MRT) and the flow structure in the vessel can be used to solve the problem of improper reactor design, understand mixing process etc. Residence Time Distribution (RTD) analysis has been recognized as the top experimental and classical tool to monitor the behavior of non-ideal chemical reactors and industrial circuits. In this current study, the aim of the research is to use the experimental RTD to determine the effect of the impeller type (axial or radial) on the Mean Residence time(MRT) and mixing, then also which model best describes the flow structure of the vessels with various impeller configurations. The method of moments was used in determining the MRT and variance from the RTD data. The MRT for the two radial flow impellers and the two axial flow impellers exceeded the theoretical MRT, however the experimental MRT of the one axial flow impeller tank and tank with no stirrers was lower than the theoretical MRT with effective volumes of 80.4% and 77.3% respectively. The two axial flow impellers showed higher variance hence better mixing than the two radial flow impellers. the and subsequent modelling of

the data using DTSPRO software to determine which flow model best describes the flow structure in the vessels when the various impellers are used. The model of best fit was the perfect mixers in series with back - mixing model which described the flow structure.



CHAPTER ONE

INTRODUCTION

1.1 Background

In many industrial and biotechnological processes, stirring is achieved by rotating an impeller in a vessel containing a fluid (stirred tank). The vessel is usually a cylindrical tank equipped with: impellers, baffles, coils, probes (e.g. thermometer, level indicators) and feed and drain pipes. All of these accessories can affect the mixing procedure (Zlokarnik, M., 2001). In most cases, baffles are mounted on the tank wall along the periphery. Their purpose is to prevent the flow from performing a solid body rotation (destroy the circular flow pattern) [Derksen et al, 1999], to inhibit the free surface vortex formation which is present in unbaffled tanks [Alcama et al, 2005] and to improve mixing. In stirred tanks, not only is the flow fully turbulent, but it is also strongly inhomogeneous and anisotropic due to the energetic agitation induced by the impeller. Three ideal flow or contacting patterns characterise ideal reactors. It is therefore the optimum goal for every reactor designer to make real reactors approach these ideals as closely as possible. The three types of ideal reactors: (a) batch reactor, (b) plug flow reactor, and (c) mixed flow reactor (Levenspiel, 1999.) Greatest numbers of the chemical reactors in the industries are non-ideal; henceforward the flow outlines in actual reactors do not follow exactly those proposed for ideal plug flow and continuous stirred vessel reactors. The nonconformity from the ideal flow outlines can be caused by channeling of fluid, by recycling of fluid, or by formation of stagnant regions in the vessel. On the other hand, the changes achieved in numerous real reactors so closely

approximate those anticipated on the basis of the ideal models that the design equations for these reactors can be utilised with insignificant error. In other situations, significant modifications are noted between witnessed and anticipated results. These differences may arise from a number of sources—from channeling of fluid as it moves through the reaction vessel, from longitudinal mixing caused by vortices and turbulence, from the presence of stagnant regions within the reactor, from bypassing or short-circuiting of portions of a packed reactor bed, from the failure of impellers or other mixing devices to provide perfect mixing, etc. Nonideal flow patterns which may occur in process equipment (Levenspiel, 1999). Generally, the flow regimes inside the vessels are controlled by: (i) the residence time distribution (RTD) of material which is flowing through the vessel (ii) the state of aggregation of the flowing material, its tendency to clump and for a group of molecules to move about together (iii) the earliness and lateness of mixing of material in the vessel. Flowing material is in some particular state of aggregation, depending on its nature. In the extremes these states can be called microfluids and macrofluids.

Mixing inefficiencies could be attributed to the multifarious nature of impeller-induced flows in stirred vessels equipped with baffles [Delvigne et al, 2005] [Raju et al, 2005]. The focus on impellers is due to the fact that they are the part of the mixer that does the actual mixing: as they rotate they create fluid flow. These flow patterns provide help in providing mass transfer of material to promote better contact between reactor contents [Rihani et al, 2009] [Kuncewicz et al, 2005]. The most common flow patterns in mixing are axial (down and up) and radial (side to side) flow. These flow patterns have effects on hydrodynamic parameters. (Mavros et al, 1996) They also describe the

generic classes of impellers: axial and radial. A good understanding of the effect of axial and radial flow impellers on mixing operations and other hydrodynamic parameters in stirred vessels will enhance optimal design and help modify existing processes which could lead to minimum capital and running costs. The hydrodynamic parameters in stirred vessels include the mean residence time (MRT), flow structure and mixing efficiency. (Aubin et al,2001)

Several experimental means to learning flow patterns in stirred vessel reactors exist [Yapici et al, 2008]. Yet, Residence Time Distribution (RTD) analysis has been recognised as the top experimental and classical tool to study the operation of non-ideal chemical reactors and industrial circuits. [Curl et al, 1966]. RTD is a probability distribution function that depicts the amount of time that a fluid element spends inside a reactor (stirred vessel). The approach is less expensive and gives reliable as well as comprehensive hydrodynamic data required to define reactor malfunction, check the legitimacy of design data and operational effectiveness of process systems. It permits an exact kinetic modeling of flow systems and aid reactor design to achieve or preserve a desired flow pattern [Haakana et al, 2008]. The RTD method is based on the inoculation of a tracer material at the inlet of the system and as it flows through the system its concentration in the outlet stream is measured as a function of time.[Feinberg et al, 2001]. The material balance of tracer at the inlet and outlet of the studied system offers a specific relationship amid corresponding concentrations. The relations are then evaluated by statistical procedures and flow model simulations to attain important information on the hydrodynamic features of the system.

Research in structure, function and principle of stirred vessels with RTD abounds, however in-depth study into the effect of impellers on the hydrodynamic parameters in a stirred vessel is inadequate; hence the focus of this study.

1.2. Problem of the research

Mechanically agitated tanks due to lower operating costs are preferred in the industries [Aubin et al, 2001]. With the goal of achieving best performance, the design of these tanks is based on the principle of an ideal mixer, which assumes instantaneous uniformity of reactor content. However, shortcomings such as insufficient mixing, excessive mixing, dead and by-passing zones prevents perfect mixing from being observed in practice, due to the large amount of material they hold, the mixing method used and the type of impellers used. These deteriorate the performance of the process [Delvigne et al, 2005]. These malfunctions do not only lower contactor efficiency, but cause deleterious effect on product quality which reduce economic benefit.

Most often industries face the challenge of deciding on which type of flow impeller to use in their stirred tanks, in order to attain better mixing. Better mixing will ensure good product quality. [Nauman, (1981)]

1.3 Research Relevance and Justification

In Ghana some work has been done using Experimental RTD to study the flow structure of stirred vessels, mixing efficiency and other hydrodynamics of Stirred Vessels. (Dagadu et al, 2012) However, much work hasn't been done using Experimental RTD to study the effect of the impeller types on the hydrodynamic parameters. Knowledge of

the mixing capabilities of the radial and axial flow impellers, will aid industries in selecting the right impeller for specific processes; hence the focus of this study

1.4 AIMS AND OBJECTIVES OF RESEARCH

To study the effect of axial and radial flow impellers on the hydrodynamic parameters of stirred tanks using experimental RTD in order to help solve the problem of improper stirred tank design, to enhance optimal design of stirred tanks and to understand the mixing process.

The Objectives of the study are:

1. Determine the RTD of the tanks containing the various flow impeller configurations
2. Use experimental RTD data to determine the effect of radial and axial flow impeller on the MRT of the stirred tank by the method of moments
3. Determine the effect of radial and axial flow impellers on mixing from statistical parameters
4. Modeling of RTD data to determine which flow model best describes the flow structure in the vessels with the different flow impeller configurations.

1.5 Scope of Research

To solve the research problem, the residence time distribution (RTD) of the various tanks with different flow impeller configurations was determined and subsequently the

mean residence time and variance were determined. To determine the flow structure of the different flow impellers in the tanks, the RTD data was simulated with different flow models using the DTSPRO software.

1.6 Outline of Research

The research work was focused on experimental RTD and modelling of the experimental RTD data. The background to the study, problem statement, and goal of the study, objectives of the study and relevance and justification of the research are presented in Chapter One. In Chapter Two, a review and detailed analysis experimental RTD method and modelling were discussed.

Chapter Three contains Research Methodologies for the determination of the RTD of the tanks with different flow impeller configurations; calculation of important statistical parameters (mean residence time (MRT) and variance). Modelling and simulation of the RTD data are also discussed in this Chapter. Chapter Four, however, presents and analyses the MRT and variance of the tanks, simulations results and the implications. The Conclusions of the study, Recommendations and Suggestions for further research are presented in Chapter Five. There are reference citation listing and Appendix.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Due to the important roles Continuously Stirred Tank Reactors (CSTRs) play in industry, various RTD studies have been conducted to better understand how they work, help improve their performance, estimate yield or validate design data.

Radiotracer Residence Time Distribution (RTD) method was used to examine the process of clinker grinding in Ghana Cement Plant (GHACEM) at Tema with the objective of determining hold-up and grinding efficiencies of two ball mills operating in close circuit regime by (Yapici et al, 2008). The experiment was done using ^{40}Ca ^{198}Au radiotracer in liquid state and extremely sensitive NaI detectors for radiation measurement. The experimental RTD data was used to approximate the mill efficiencies and this revealed while one mill operated with optimal performance the other was far below expectation.

Also (Sugiharto et al, 2009) applied radiotracer to investigate RTD in multiphase flow system which included 95% water, 3% crude, 2% gas and negligible solid material. Results from this experiment explained why crude oil always arrives behind water as it is checked at gathering station though crude oil is less dense relative to water.

(Dagadu et al, 2012) used both the online and sampling method of radiotracer studies to measure the RTD of aqueous phase in a series of gold leaching tanks at the Damang gold processing plant in Ghana after a process intensification or revamping

of the plant with the aim of measuring the effective volume of each tank and validating the design data. The estimated effective volume of the tanks and high degree of mixing in tanks was used to validate the design data and confirmed the expectation of the plant engineer after intensification of the process.

The mixing limitations of a process stream can be assessed by RTD thus helping the process engineer better understand performance of a chemical reactor. In 2004, Ham et al. modelled flow patterns in an industrial scale reactor with a plunging jet inlet and optimal agitation. The objective of this study was to quantify RTD under different operating conditions of liquid level, throughput and agitation. The reactor RTD was obtained from stochastic particle tracking which tracks residence times of massless tracers through the reactor. The predicted mean residence times were consistent with the bulk reactor space times.

(Scargiali et al, 2007) obtained experimental information on the retention time distribution (RTD) of solid particles in a high-aspect-ratio vessel, stirred by three equally spaced Rushton turbines. The RTD data obtained indicated that a cascade of ideally mixed tanks with backflow results into very good agreement with experiment, with practically any number of tanks in series but one, provided that the backflow rate parameter is chosen accordingly. In all cases, the recirculation is large enough for the resulting flow model to be quite close to a single perfectly stirred vessel.

2.1.1 Mixing Phenomena

The purpose of mixing is to ensure homogenization, manifesting itself in a decrease of concentration or temperature gradients or both simultaneously, within the agitated system. Quillen describes mixing as the ‘intermingling of two or more dissimilar portions of a material, resulting in the attainment of a desired level of uniformity, either physical or chemical, in the final material.

Gases, restrained in a container, mix swiftly by natural molecular diffusion. In liquids, however, natural diffusion is a slow procedure. To speed up molecular diffusion in liquids, the mechanical energy from a rotating agitator is adopted.

The constant rotation of an agitator in a confined liquid mass produces eddy currents (Chapman et al, 1964). These are created due to velocity gradients within the liquid. A rotating agitator induces high velocity liquid streams, which move through the vessel (Julian et al, 2012). When the high velocity streams come into contact with stagnant or slower moving liquid, momentum transfer occurs. Low velocity liquid becomes entrained in faster moving streams, resulting in forced diffusion and liquid mixing (Joanna et al, 2009).

The extent of mixing within a system is a property of two variables: (1) the intensity of eddy currents or the level of turbulence formed and (2) the contrary forces tending to dampen this formation. The higher the ratio of applied to dampening forces, the higher the degree of mixing. This relationship may be expressed by the well known rate equation by (Milovanovic et al, 2009).

$$\text{Flow rate} = \frac{\text{Driving force}}{\text{Resistance}} \quad (2.1)$$

Driving force is the forces producing eddy currents or turbulence whilst *resistance* is the forces tending to dampen the formation of eddy currents or turbulence, and the *flow rate* refers to the degree of mixing.

A high degree of mixing occurs when the entire liquid mass, confined in a vessel, is under turbulent flow condition. The amount of mechanical energy required to extend turbulence all the way through a liquid mass depends upon (1) Vessel geometry (2) Agitator geometry and (3) The physical properties of the liquid(s) being mixed (Letan et al, 2004).

2.2 Agitation

Agitation is the process of providing bulk motion to a liquid, thus aiding mixing and dispersion. Agitation of liquids is usually accomplished in a container equipped with an impeller such as a propeller, paddle or turbine. The impeller is inserted into the liquid and rotated in such a manner as to cause both bulk motion and fine scale eddies in the fluid. Mechanical energy is required to rotate the impeller, which in turn transmits the energy to the fluid. In the process of agitation, the impeller is rotating; the sides and the bottom of the tank are stationary, and the resultant velocity gradient cause mixing.

The mixing of fluids in agitated vessel is one of the most important unit operations for many industries including the chemical, bio-chemical, pharmaceutical, petrochemical, and food processing. Therefore determining the level of mixing and overall behaviour and performance of the mixing tanks are crucial from the product quality and process economics point of views (Armenante et al 1997). A typical stirred vessel consists of three parts: tank, baffles and impeller as demonstrated in figure 2.1.

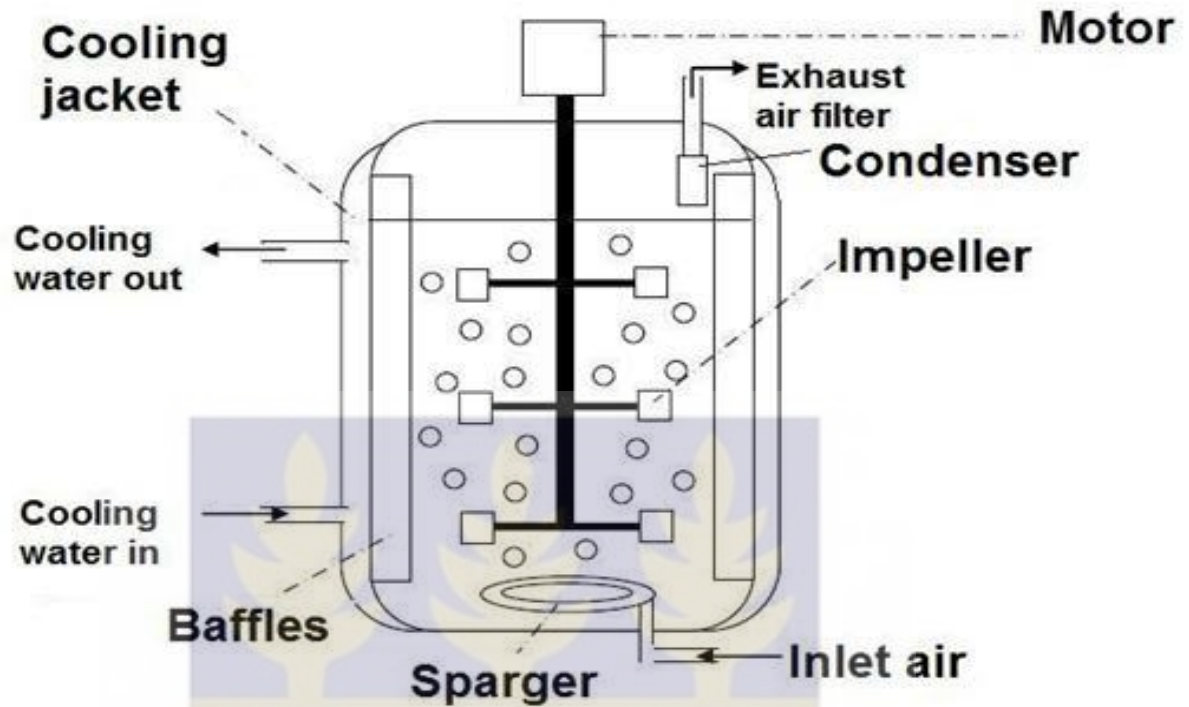


Figure 2. 1: A typical stirred tank for mixing fluids

Baffles are important parts of the stirred tanks which improve the mixing efficiency and suppress the vortex formation. However they increase the power requirements in the mixing tank. Several baffle arrangements are available according to their using purposes. For example they can be fixed on the tank wall or can be set away from the wall.

2.3 Impellers

Impeller is used to produce centrifugal force to create the mass transfer between the various phases by mixing. Mixing of phases can be accomplished and by which mass and heat transfer can be enhanced between phases or external surfaces. The operation of agitation, which includes mixing as a special case, is now well established as an

important and in a wide variety of chemical processes. Specifically, impellers are applied to three general classes of problems;

- (i) To produce static or dynamic uniformity in multicomponent multiphase systems
- (ii) To facilitate mass or energy transfer between the parts of a system not in equilibrium
- (iii) To promote phase changes in multicomponent system with or without a change in composition (Sahu et al, 1998)

2.3.1 Types of Impellers in Stirred Tanks

2.3.1.1. The helical screw agitator

The helical screw agitator is an effective device when used in high viscosity liquids (Chapman, 1962). The screw functions by carrying liquid from the vessel bottom to the liquid surface. The liquid is then discharged and returns to the tank bottom to fill the void created when fresh liquid is carried to the surface.

2.3.1.2. Anchor impeller

The anchor agitator is generally a slow moving, large surface area device; in close proximity to the vessel wall. It has been used in the batch mixing of liquids having high viscosity.

2.3.1.3 High shear impeller

High shear agitators are primarily used in liquid mixing systems where a particle size reduction or a breaking apart of agglomerated solids is required.

2.4 Flow patterns in Stirred Tank

The impellers are also classified according to the flow pattern i.e. axial flow and radial flow. There are Impellers based on axial type such as Propeller, Paddle and Curved.

Some Impellers are also based on radial type such as Paddle, Turbine, Pitched, Helix and Curved.

2.4.1 Axial Flow

Axial flow discharge coincides with the axis of impeller shaft, so when the impeller operates in a down pumping mode, the flow impinges on the bottom of the tank and spreads out in all directions toward the wall. The flow rises along the walls up the liquid surface and is pulled back to the impeller. Since axial flow impeller produce only one loop, fluids mix faster and blend time is reduced compared to radial flow impellers. The fluid does not take sharp turns near impellers and because of this, power consumption is less than that of radial flow impellers at the same speed and same diameter.(Bouanini et al,2008).

2.4.2 Radial Flow

Radial Flow discharge is parallel to the impeller radius toward to the vessel wall. If a radial impeller is not positioned close to the surface or the tank bottom, the flow will

split into two streams upon impinging on the tank wall. Each flow loop will continue along the wall and then return to impeller.

2.5 Residence Time Distribution (RTD)

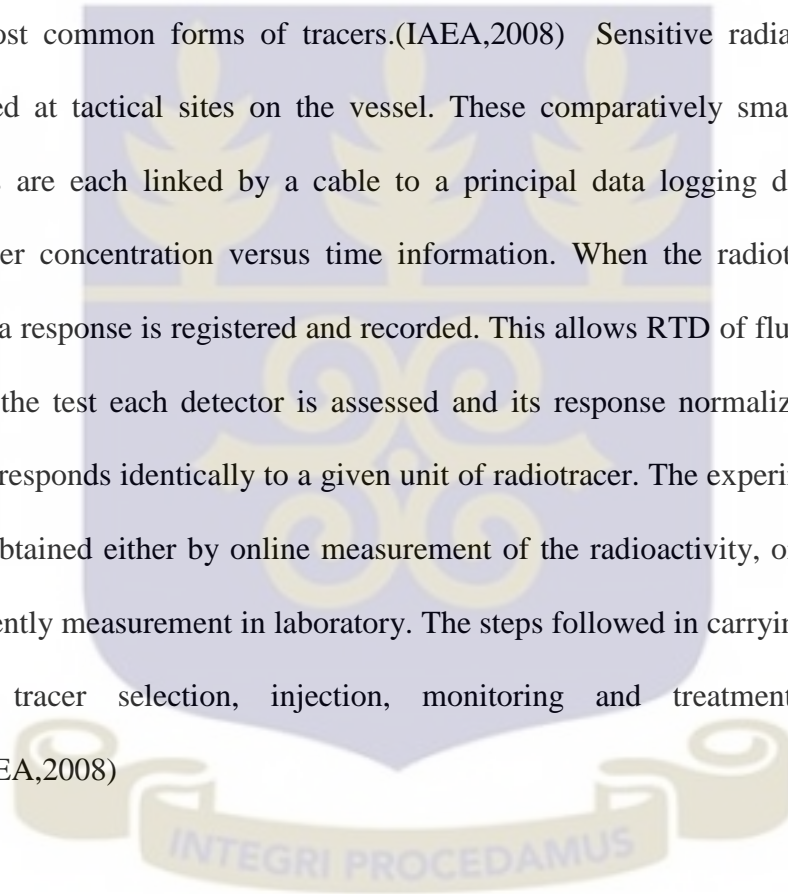
The idea of using the distribution of residence times in the analysis of chemical reactor performance was apparently first proposed in a pioneering paper by MacMullin and Weber, (1935). However, the concept did not appear to be used extensively until the early 1950s, when Prof. P. V. Danckwerts, (1953) gave organizational structure to the subject of RTD by defining most of the distributions of interest.

The residence time distribution (RTD) of a chemical reactor is a probability distribution function that describes the amount of time a fluid element could spend inside the reactor. The RTD is used to describe the mixing and flow within vessels and to liken the performance of real reactors to their ideal models. This isn't only useful for troubleshooting current reactors, but in approximating the produce of a given reaction and designing future reactors. The idea of residence time distribution (RTD) has become a vibrant technique for the study of industrial entities and reactors. (Jean-Pierre et al, 2007). The RTD of fluid flow in process equipment defines their performance.

2.5.1 Determination of Residence Time Distribution

The RTD is obtained experimentally by introducing a nonreactive chemical substance, called a tracer, into the reactor at a specified time and then determining the tracer

concentration, C , in the outlet stream as a function of time. In addition to being an inert entity that is effortlessly detectable, the tracer should have physical properties comparable to those of the reacting mixture and be entirely soluble in the mixture. It also should not adsorb on the walls or other surfaces in the reactor. The later requirements are required so that the tracer's conduct will reliably replicate that of the material flowing through the reactor. Colored and radioactive materials along with rare gases are the utmost common forms of tracers.(IAEA,2008) Sensitive radiation detectors are positioned at tactical sites on the vessel. These comparatively small and easy to fix detectors are each linked by a cable to a principal data logging device that records radiotracer concentration versus time information. When the radiotracer passes each detector a response is registered and recorded. This allows RTD of fluid to be measured. Prior to the test each detector is assessed and its response normalized such that each detector responds identically to a given unit of radiotracer. The experimental RTD curve can be obtained either by online measurement of the radioactivity, or by sampling and subsequently measurement in laboratory. The steps followed in carrying out an RTD test involve tracer selection, injection, monitoring and treatment of the tracer data.(IAEA,2008)



2.5.2 Chemical Tracers

A tracer is any substance whose atomic or nuclear, physical, chemical, or biological properties provide for the identification, observation and following of the behavior of various physical, chemical or biological processes (dispersion, mixing, kinetics and dynamics), which occur either instantaneously or in a given lapse of time (IAEA, 2008). For a tracer to be selected, changes in their concentration must not affect the behavior of the main population, and these changes in concentration must be measurable. Also they must exhibit the properties of the investigated process stream be detectable by a particular physico-chemical property such as color, radioactivity and conductivity. The use of tracers like dyes, soluble salts, electrolytes and magnetic materials is a well-known method for the study and diagnosis of the CSTR. (IAEA 2006)

2.6 Radioactive Tracers

A radioactive tracer is a chemical compound in which one or more atoms have been replaced by a radioisotope so by virtue of its radioactive decay it can be used to explore the mechanism of chemical reactions by tracing the path that the radioisotope follows from reactants to products. (Berne et al,1998)

Radiotracers are used to obtain hydrodynamic parameters such that the mean residence time (MRT) and the residence time distribution (RTD) curve which are analyzed in order to understand the operation of the vessel. The success of the radiotracers applications is mainly due to the possibility, offered by the unique properties of the

radioactive materials, to collect data which cannot be obtained by other techniques of investigation (Margrita, 1983).

2.6.1 Radioactive Tracer Selection

The factors that must be satisfied in the selection of a given radiotracer are given as follows:

a) **Physico-chemical properties of the tracer with respect to the system in question.** The first factor to be considered is that the radioactive isotopes of a given element behave identically as the stable isotopes of the same element. According to IAEA (2006), when tracing elements or compounds in structures where there are no chemical transformations, the radiotracer does not have to be chemically characteristic of the element or compound. The designated radiotracer must be able to tail the process stream from the point of injection to the point of detection without being neutralized by any component of the process stream or adsorbed on the walls of the process vessel.

b) **Half-life of tracer**

Radioactivity is measured in Curie units. One Curie (Ci) is defined as the quantity of a radioactive nuclide in which the number of disintegrations per second is 3.700×10^{10} . Radioisotopes of a very short half-life are less useful as tracers for analytical purposes, since they disappear during the quickest chemical operations. The best tracers for chemical purposes are those with half-lives between, say, a few weeks and a few years. The very long-lived ones present the

intrinsic disadvantage of having low sensitivity because of the relatively large mass associated with low activities. (IAEA, 2006)

c) **Specific Activity of Tracer**

The specific activity of a sample of a radioactive substance is the ratio of its activity to its mass (or volume of solution, or moles, or any convenient unit proportional to its mass) and gives a relative measurement of the strength of the sample. The specific activity of a pure radioisotope is the maximum value attainable for the nuclide concerned. (Toye et al, 1996)

In analytical applications it is convenient in general to have as high a specific activity as possible to improve the sensitivity of the detection and, therefore, carrier-free isotopes should be preferred. For practical purposes, the specific activity is expressed in counts per minute/unit mass for a particular measuring procedure. This is a fraction of the absolute activity of the sample in disintegrations per minute/unit mass, the value of this fraction depending on the efficiency of the counting arrangement. Comparative values are obtained by adhering strictly to the same measuring procedure when following the fate of a tracer in one experiment, (IAEA, 1999)

d) **Cost of Tracer**

Cost is also an important factor in tracer selection. The prices of radioisotopes vary widely for many reasons (production in nuclear reactors or in accelerators, activation of natural elements or of stable isotopes artificially separated, etc.) and frequently the 'second-best' nuclide will cover the necessities at much less expense, (IAEA, 1999)

e) **Availability of Tracer**

Radioisotopes can be ordered from producers or authorized distributors in most countries. Even small research reactors can produce about 30 shortlived useful ones. Local regulations as to its free use vary from country to country, but in general an authorization from the national atomic energy authority is required. In tracer use for chemical purposes, the activities involved are small and there is usually no difficulty to obtain that authorization provided that evidence of the necessary expertise in the laboratory can be proved. (IAEA, 2008)

f) **Energy of radioactive particle emitted by Tracer**

The type and energy of the emitted radiation are very crucial from the detection point of view. Gamma emitting radiations are used. Gamma emitting radiotracers are employed in most industrial investigations. (Pant et al, 2011). The energy should be sufficiently high to penetrate through the wall of the system and get detected. (IAEA, 2009) Gamma-ray emitting radionuclides are preferred for most industrial applications because of the ability of gamma radiation to penetrate the often substantial thicknesses of material from which process plant is constructed. Gamma rays of energy 140 keV and upwards have been found to be useful. (IAEA,2006).

2.6.2. Experimental Residence Time Distribution (RTD)

2.6.3. Tracer Injection

Tracer injection is done in a specific fashion. The three main ways of injecting radiotracers in RTD experiment are: Dirac signal, Step signal and more complex

signals (Sine waves or other cyclic signals). In most RTD investigations tracer is introduced either as a Dirac signal or a step signal. These two fashions of tracer dosing, unlike the more complex signals do not result in complex outlet functions involving laborious numerical calculations.

2.6.3.1. Dirac Injection

According to Brouyère and Dassargues (2002), Dirac injection involves instantaneous (impulse) introduction of tracer in a very short time. See figure 2.2. Theoretically the duration is considered less than 3% of the MRT of the system. Some of the important considerations in Dirac injection are, the use of a small amount (shot) of tracer makes impulse injection more cost effective and also, the outlet response after the necessary data treatment procedures, represents the RTD of the system. (IAEA, 1999)

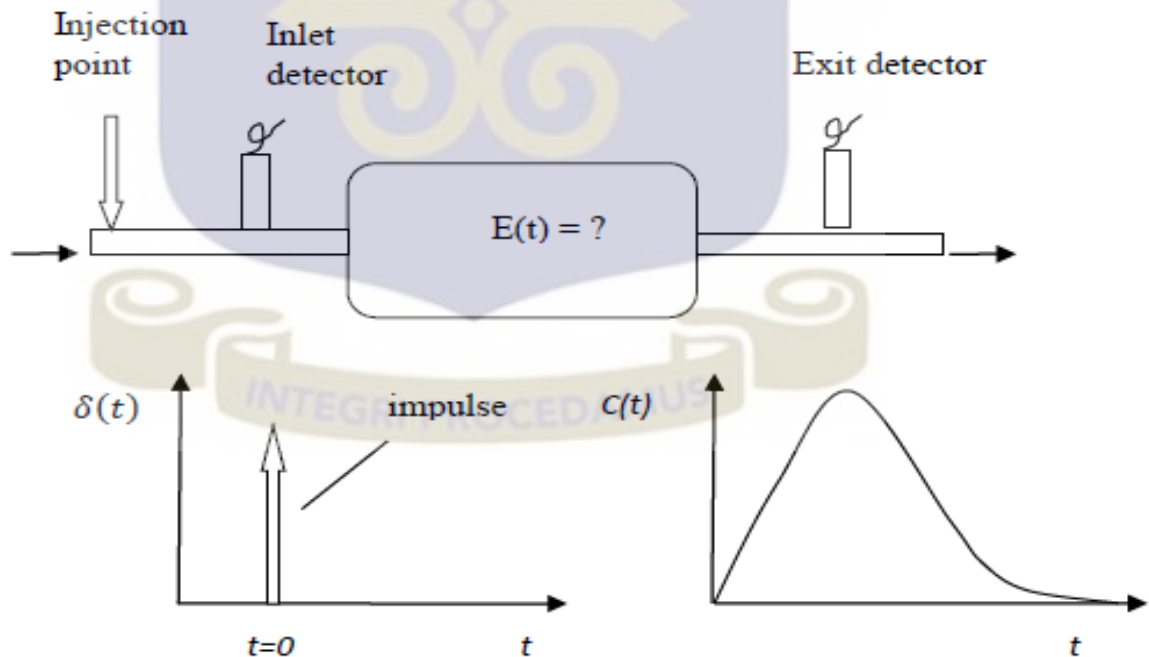
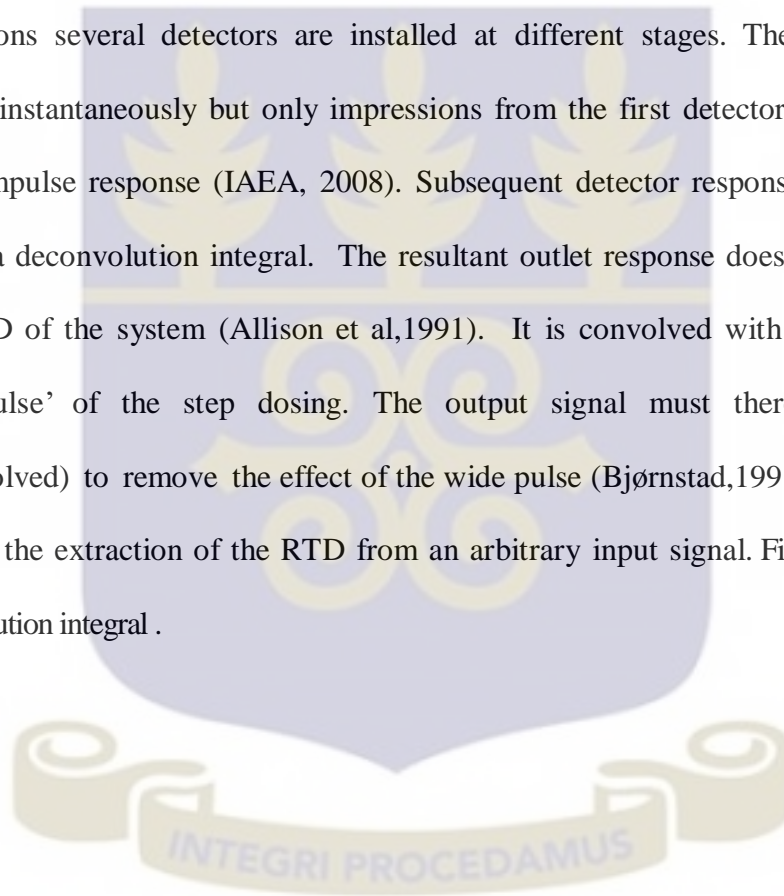


Figure 2. 2: Shows diagram for Dirac injection (IAEA, 2008)

2.6.2.2 Step Injection

In Step injection case the tracer is introduced continuous for a longer period of time unlike the impulse dosing. This is usually done in situations where tracer cannot be introduced directly into the inlet of the studied system but rather at a different location or when the system consists of a cascade connection of reactors. In cascade connections several detectors are installed at different stages. The tracer could be injected instantaneously but only impressions from the first detector can be measured as the impulse response (IAEA, 2008). Subsequent detector responses are filtered by solving a deconvolution integral. The resultant outlet response does not represent the true RTD of the system (Allison et al,1991). It is convolved with the signal of the ‘wide pulse’ of the step dosing. The output signal must therefore be filtered (deconvolved) to remove the effect of the wide pulse (Bjørnstad,1991). Deconvolution involves the extraction of the RTD from an arbitrary input signal. Figure 2.3. shows the deconvolution integral .



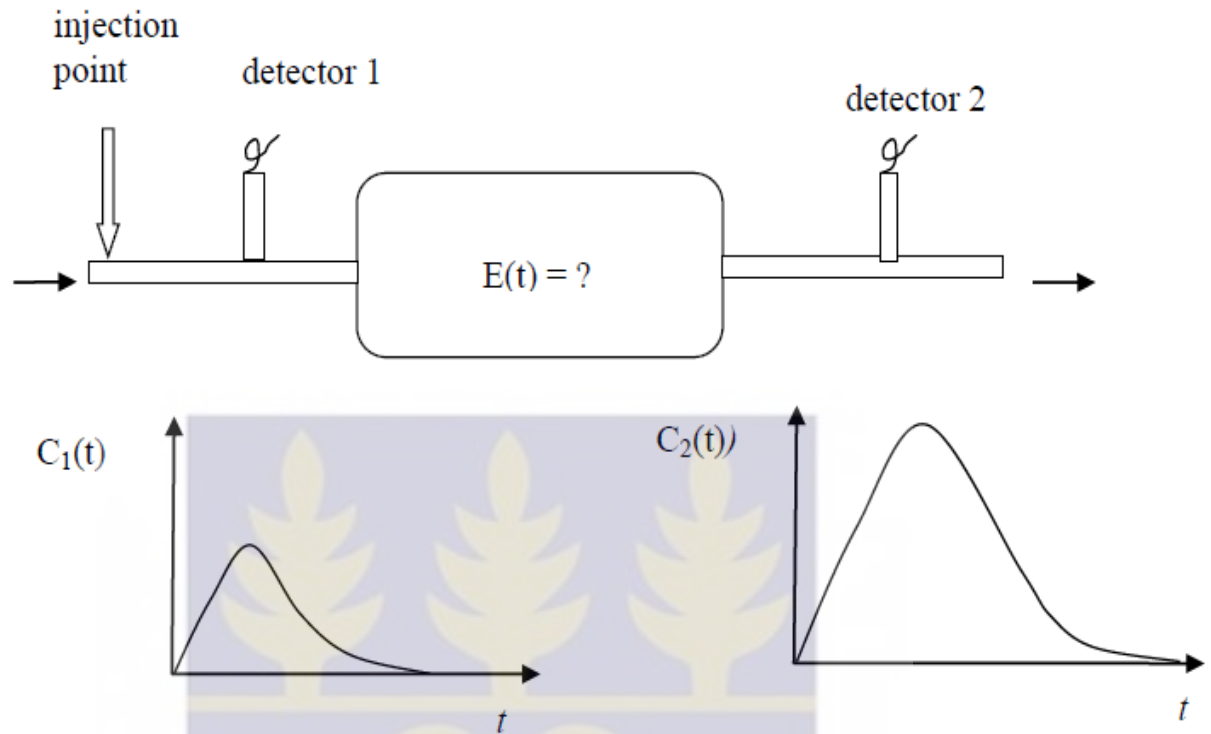


Figure 2. 3: Shows diagram for step injection

For a step injection at time $t = u$, the response at the outlet will be given by the function $E(t)$ shifted by time u as demonstrated in equation (2.2)

$$C_2(t) = \int_0^{\infty} C_1(u) E(t - u) du \quad (2.2)$$

2.6.4. Tracer Monitoring

The concentration of a radiotracer in the exit stream of a system can be determined by two methods:

Sampling: taking samples of the investigated media and later counting the samples using a suitable radiation detector.

On-line: radiation detectors are installed at the exit stream to monitor tracer concentration directly, (IAEA, 2008).

2.6.5 Data Acquisition in RTD Experiments

Two detectors are needed for normal radiotracer experiments, such as measurement of the residence time distribution (RTD) of the radiotracer inside a reactor (inlet-outlet response), flow rate measurement or leak detection in a simple heat exchanger, (IAEA, 2011).

The most common probe is NaI(Tl) detector in waterproof casing. They are very sensitive sensors to gamma radiation, for example a 1''x 1'' NaI (Tl) scintillation detector for ^{82}Br measured in water with an infinite detection geometry condition gives 65 cpm/kBq/m^3 , (IAEA, 2009) The probes are mounted in selected places at the inlet and outlet of the processing vessel shielded around by collimators to protect them from the parasite radiation coming from around (IAEA, 2009). The injection of tracer into the vessel is performed by special injectors designed for liquid or gas flows under different pressures. Detector protection from reactor heating is realized by aluminium plate placed between the detector and reactor walls (IAEA, 2009).

2.6.5. Treatment of Tracer Data

Data collected from a radiotracer examination is usually affected by statistical variations and other parasite influences. Therefore, some quantity of treatment must be applied to the documented signals before further study or modeling (Zemel, 1995).

2.6.7.1 Correction of Background Radiation

The influence of the background radiation to the data, due to industrial sources in the form of nuclear gauges, must be eliminated. Previous to the inoculation of radiotracer into a system, it is essential to measure the background radiation level, which is deducted from the experimental data. The correction of background radiation can be carried out by the relation below.(IAEA,2008)

$$C(t_i) = C_{exp}(t_i) - C_{bkg} \quad (2.3)$$

2.6.7.2 Data Filtering (Smoothing)

The purpose of filtering is to eradicate, or at least lessening, vacillations due to counting statistics or electronic noise. Several methods are available. The Fourier transform is very effective; many high frequencies can be filtered without altering the general shape of the RTD experimental curve. The Fourier method requires that the data be sampled at equidistant (regular) intervals. Cumulating or resampling counts is simpler technique for levelling fluctuations. Counts are cumulated by groups of 5, 25 and 100, (IAEA, 2008).

2.6.7.3 Dead time Correction

In order for two gamma photons to be registered by the detector as two separate pulses, they must be separated by a minimum amount of time. This minimum time

delay is known as dead time. Dead time may be as a result of either the physical detection process or the associated electronic devices (Potier et al, 1999).

2.7.1 Decay Correction

This is done when the duration of the experiment relative to the half-life of the radioactive tracer, is long. In this case undue weight is given to earlier measurements. Since radioisotope tracers decay exponentially with time, it is necessary to apply decay correction to the measured data (Niemi et al, 1999).

$$\begin{aligned} C(t_i) &= C_{exp}(t_i) \exp(\lambda t) \\ &= C_{exp}(t_i) \exp \frac{0.693t}{T_{1/2}} \end{aligned} \quad (2.4)$$

Data extrapolation is needed when the end of the tracer curve is missed, or, in other words, count rates return to zero after the end of the data acquisition sequence. Frequently extrapolation is done mathematically using exponential decay function. The purpose of data extrapolation is to lengthen the tracer curve in some plausible way. The most common way is to check that count rates decline exponentially at the end of the experiment; this is easily done by plotting the logarithm of count rates versus time, which should exhibit a linear behavior towards the end. A decaying exponential function should then be adjusted on that part of the curve, and the data extended with this function until count rates are negligibly small. The number of extrapolated points should obviously be “reasonable” (the meaning of “reasonable depends very much on available data and level of precision desired). (IAEA, 2008)

2.7.2. Area Normalisation

Prior to data analysis, it is a compulsory to convert the count rates into RTD functions represented by $E(t)$. The $E(t)$ function is obtained by dividing each data point under the $C(t)$ curve by the area. The $E(t)$ function is given by:

$$E(t) = \frac{C(t)}{\int_0^{\infty} C(t) dt} \quad (2.5)$$

Integrating equation (2.5) leads to

$$\int_0^{\infty} E(t) dt = 1 \quad (2.6)$$

This operation helps to eliminate all factors such as injected activity and radiation attenuation by walls that affect the area of the curve but not its shape (IAEA, 1996). It also allows for easy calculation of the valuable statistical parameters (residence time, MRT) and is therefore compulsory for data modeling.

Area Normalised curves include the following curves is shown in figs. (2.4)



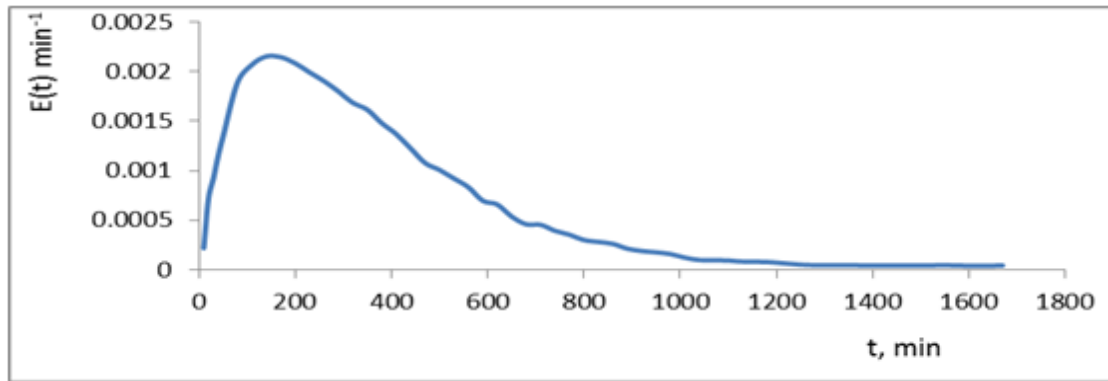


Figure 2.4(a): Example of Area Normalised curve

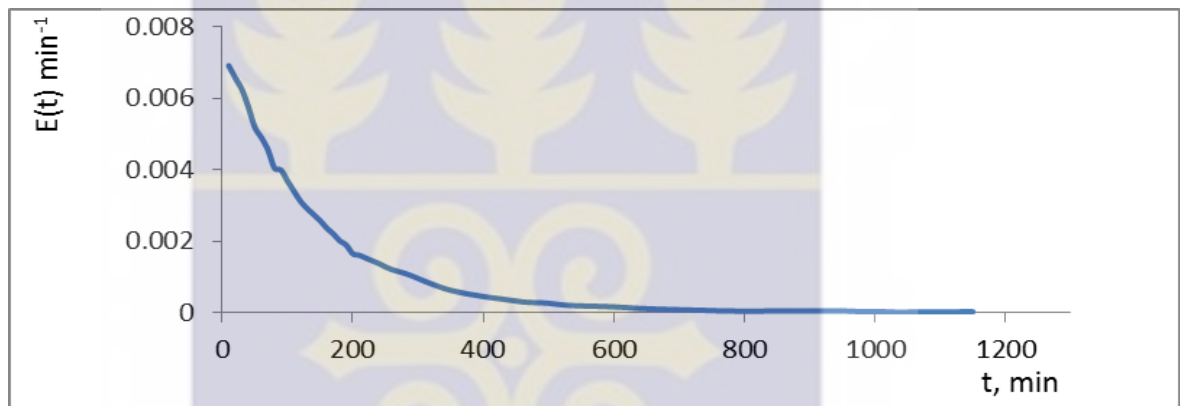


Figure 2.4(b): Example of Area Normalised curve

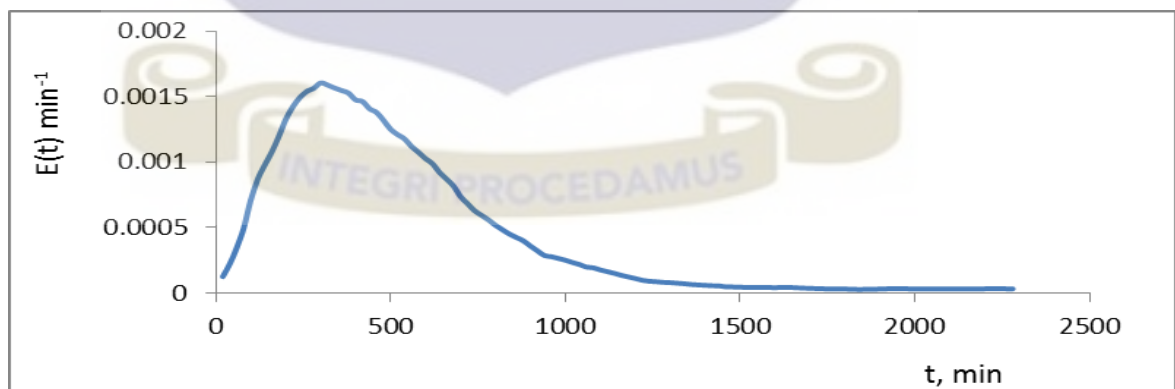


Figure 2.4(c): Example of Area Normalised curve

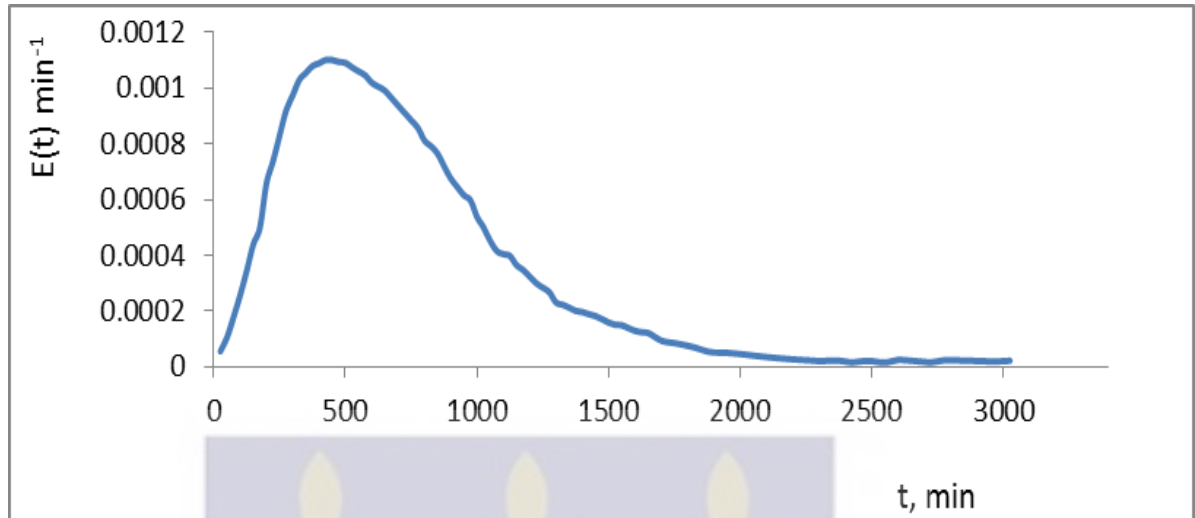


Figure 2. 4(d): Example of curve normalization

2.7.3 Data Analysis

There are three interconnected ways to extract useful information from the E(t) curve.

1. Observing the shape of the curve in terms of tailing effect and number of peaks etc.
2. Evaluation of the useful statistical parameters (MRT and its variance)
3. Modelling: comparison of the experimental data with a suitable mathematical description of flow.(IAEA, 1996)

For normal operating systems, the counting rate should return to zero (background) after 2 or 3 theoretical MRTs. However, in the presence of anomalies such as stagnant zone the values could increase by 5–10 times resulting in long tailing of the curves.

2.7.4. Evaluating of Statistical Parameters

The most important statistical parameters are MRT and Variance which are calculated from the method of moments. (IAEA,2008) The method of moments is considered the simplest RTD data analytical method. It is an approximate technique for solving the differential equations of the distribution functions. The first moment of the distribution curve represents the MRT. The MRT describes the central location of the output RTD data and is given as:

$$\bar{t} = \int_0^{\infty} t E(t) dt \quad (2.6)$$

The variance is a measure of the statistical dispersion (spread) of the RTD. It expresses the average squared distance of its possible values from the expected values (mean) and is given as:

$$\sigma^2 = \int_0^{\infty} (t - \bar{t})^2 E(t) dt \quad (2.6.1)$$

where

$$\bar{t} = \int_0^{\infty} t E(t) dt \quad (2.6.2)$$

2.8. Modelling

Flow models are theoretical functions characterized by a known flow structure used to reveal the hydrodynamic characteristics of a system of unknown internal flow structure by comparing the experimental data of the studied system with the mathematical relations describing the model. To be able to define the flow structure in the studied vessels, mathematical models are used to simulate the experimentally obtained RTD data. The flow models are grouped into elementary models and combined models. The elementary models are made of two ideal models and two non-ideal models whereas the combined model is a combination of two or more elementary models. Flow modeling is performed using software packages within which many reactor models are encoded. E.g. DTSPRO(IAEA,2008)

2.8.1 Ideal Models

The ideal models represent two extreme circumstances, where mixing is either non-existent or directly whole. (IAEA,2008)

2.8.1.1 Plug Flow Reactor model (PFR)

The flow of fluid through a system takes place without dispersion. Thus, the flow is orderly with no element of fluid overtaking or mixing with any other element ahead or behind. A Dirac injection is transported without deformation but shifted by a time-lag τ .

2.8.1.2 Perfect Mixer (PM) model

The PM model assumes instantaneous mixing of the input material with the material already in the system. The material composition in the whole system including the output stream is the same. The flow is represented by the expression

$$E(t) = \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) \quad (2.7)$$

Time constant τ which is the model parameter can be calculated from the first moment (MRT) of the distribution curve. Shown in fig.(2.5), (IAEA, 2008)

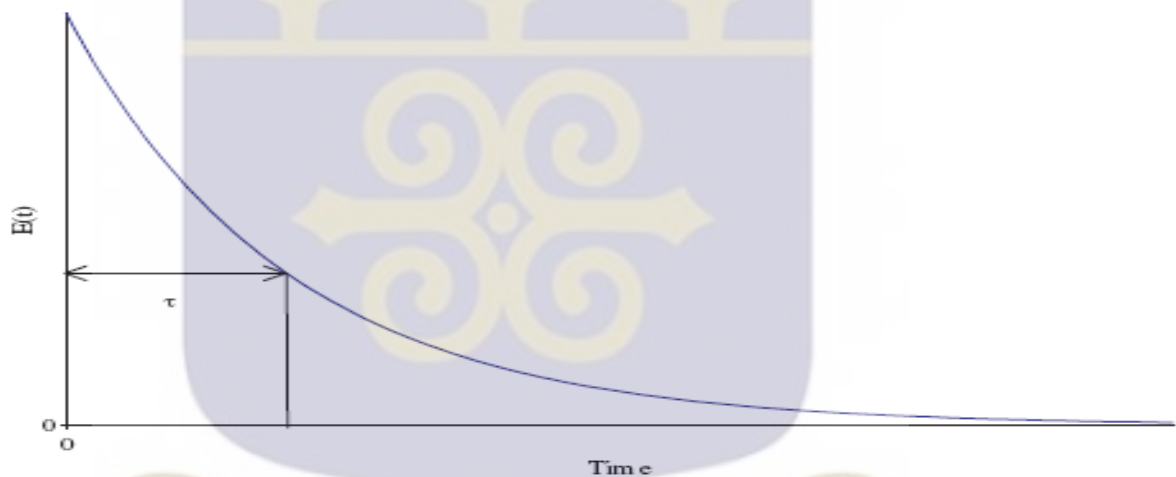


Figure 2. 5: Shows first moment (MRT) of the distribution curve

2.8.2. Non-ideal model

Contrary to the ideal conditions, practical systems are characterised by non-ideal flows that are intermediates between the extremes of the two ideal models. Two non-ideal flow models basically used to analyse practical reactors are: Axial Dispersion Model (ADM) and Perfect Mixers in Series Model (PMSM) (IAEA, 2008)

2.8.2.1 Axial Dispersion Model (ADM)

The ADM suggests that the spread (mixing) of a flowing fluid is due to two factors; longitudinal dispersion of flow due to convective bulk motion of the fluid and diffusive random motion of fluid element in response to the decay of turbulent eddies.

The spread is, therefore, a diffusion- like process or back mixing superimposed on plug flow.

This type of flow is mainly observed in systems symmetrically designed with very large length- to-diameter ratios. The ADM is, therefore used to study systems in which the flow structures do not differ very much from plug flow namely long pipes, fluidized beds and packed columns.

The equation characterizing this model is given as

$$E(t) = \frac{1}{2} \left(\frac{Pe}{\pi \tau t} \right)^{\frac{1}{2}} \exp \left(- \frac{Pe(\tau - t)^2}{4\tau t} \right) \quad (2.8)$$

Parameters: τ and Pe .

MRT (1st moment) = τ , Pe = pecklet number

Variance (2nd moment) $\sigma^2 = (2. \tau^2)/P$

2.8.2.2 Perfect Mixers in Series (PMS) Model

The PMS model is also known as tanks-in-series model. Shown in Fig.(2.6). It is an alternative to the ADM where the fluid is viewed as being flowing through a series of equal size completely mixed compartments. (IAEA,2008)

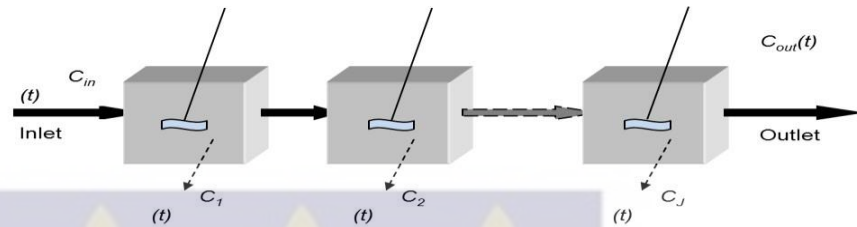


Figure 2. 6: Conceptual representation of perfect mixers in series model

2.8.3. Combined models

Complex industrial systems are characterized by the so called parallel flows that adversely affect the performance. Notably among these parallel flows are bypassing (channelling), back flow and active and stagnant regions. Even though the two non-ideal flow models have been extensively used to quantify reactor non-ideality, the information they provide is often not sufficient to understand parallel flows thus the concept of combined models come in handy. This is achieved by combining the elementary models into more complex units to study the complex flow systems characterized by “parallel flows” within the vessel. The elementary models can be combined in many ways depending on the nature of the experimental curve and the design features of the flow systems. (IAEA,2008)

2.8.3.1 Perfect mixers in series with exchange (PMSE) model

This model is an addition of the perfect mixers in series model; each perfect mixer is now connected to another with an exchange flow rate of αQ . As seen in



CHAPTER THREE

METHODOLOGY

3.1. Introduction

Experimental work was conducted using the flow rig at the Radiotracer Laboratory of Ghana Atomic Energy Commission. Below is the description of the flow rig.

3.2. The Flow Rig experimental setup description

Flow rig is a laboratory set up for demonstrating radiotracer test in various conditions of flow rate and flow models. The schematic set-up is shown in Figure 3.1. The flow rig is made up of a one High Pressure (1-HP) water pump, a flow meter, a water filter and four stainless steel tanks numbered 1 to 4. These are connected together by a network of 1-inch polyvinylchloride (PVC) pipes. Each of the stainless steel tanks has a height of 59.5 cm and a diameter of 35.0 cm. Six detectors, with collimators, were installed at the influent and effluent of tanks 1, 2 and 4. These six detectors are respectively connected to the first six channels of the data acquisition system. The first three tanks contain agitators with tank 1 having one (1) axial impeller (Figure 3.6), tank 2 having two(2) axial impellers (Figure 3.7), tank 3 having two(2) radial impeller (Figure 3.8) and tank 4 having no agitators (Figure 3.9). Water is supplied to the flow rig from a 1000L PVC water tank (Figure 3.3), installed outside the radiotracer laboratory, through the 1-hp water pump. A flow meter was installed between the 1000L PVC water tank and the 1-hp water pump to measure the flow rate of water drawn from the 1000L PVC water tank. Water pumped from the 1000L PVC water tank goes through a water filter and a second flow meter, installed just

after the 1-hp water pump, to tank 1. By gravity, water from tank1 then flows through tanks 2, tank 3 and then to tank 4. Effluent water from tank 4 goes into another 1000L PVC water tank also installed outside the radiotracer laboratory (Figure 3.4).

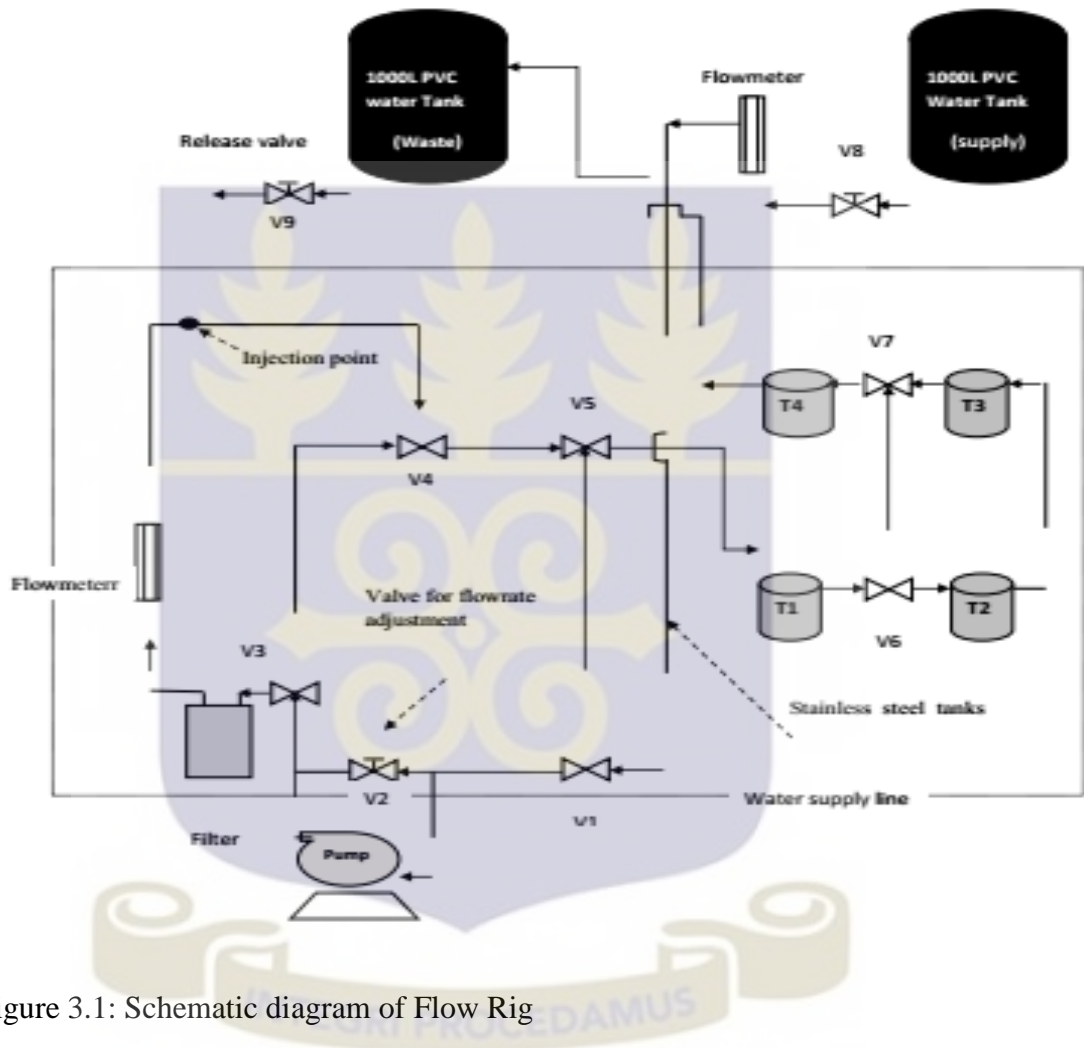


Figure 3.1: Schematic diagram of Flow Rig



Figure 3. 2: Flow rig experimental setup



Figure 3. 3: The 1000L PVC water Tank that supplies water to the Flow Rig



Figure 3. 4: The 1000 L PVC water Tank for storing water from the Flow Rig



Figure 3. 5: The Injection unit



Figure 3. 6: tank1 showing one axial flow impellers



Figure 3.7: Tank2 showing two axial flow impeller



Figure 3.8: Tank3 showing two radial flow impeller

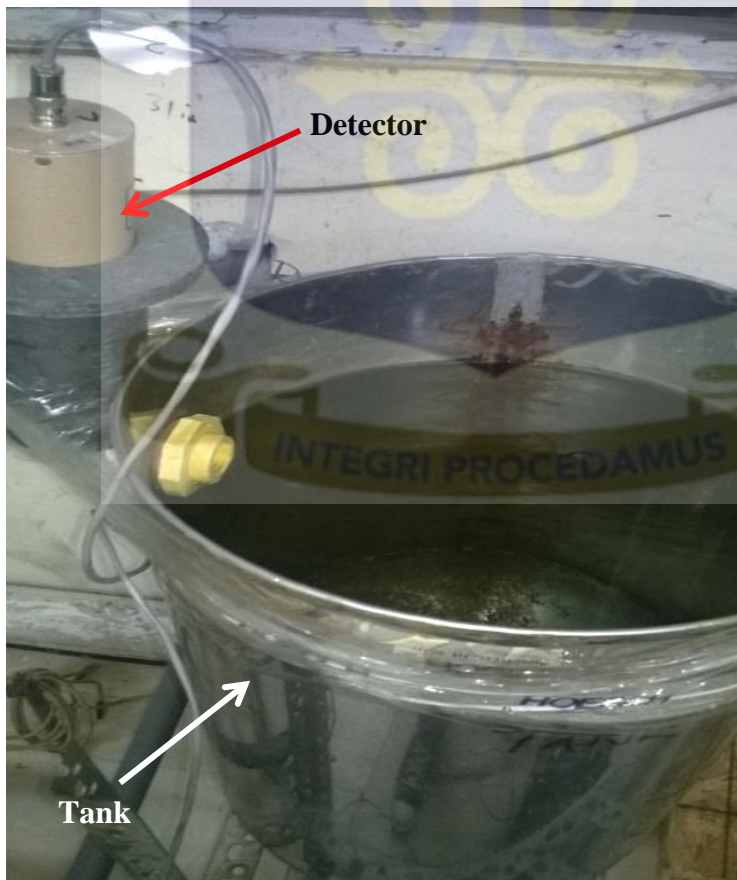


Figure 3.9: Tank4 with no stirrers

3.3. RTD Experiment

Due to the arrangement of the tanks in the flow rig, thus four tanks in series, the experiment was conducted at the same time using the same radiotracer that was injected into the process stream. For every radiotracer studies, the first most important on the list is the selection of an applicable tracer for the experiment.[IAEA 2008]

3.3.1. Selection of applicable tracer

For this current study, Gamma radiation emitter Technetium (Tc-99m) in the form of Sodium pertechnetate (TcO_4^-) with half life of 6 h, activity of 75mCi and energy of 0.14MeV (90%) was used as a tracer. The energy of the gamma radiations was sufficiently high to penetrate through the wall of the system and get detected. The duration of the experiment was one(1) hour. [IAEA 2008] [IAEA, 2000].

3.3.2. Tracer injection

In most RTD investigations tracer is introduced either as a Dirac signal or a step signal, [Charlton, 1986]. In the current study, the tracer was introduced as a Dirac signal. Dirac injection of Tc-99 involved the instantaneous (impulse) introduction of the tracer in a very short time (Figure 3.10).

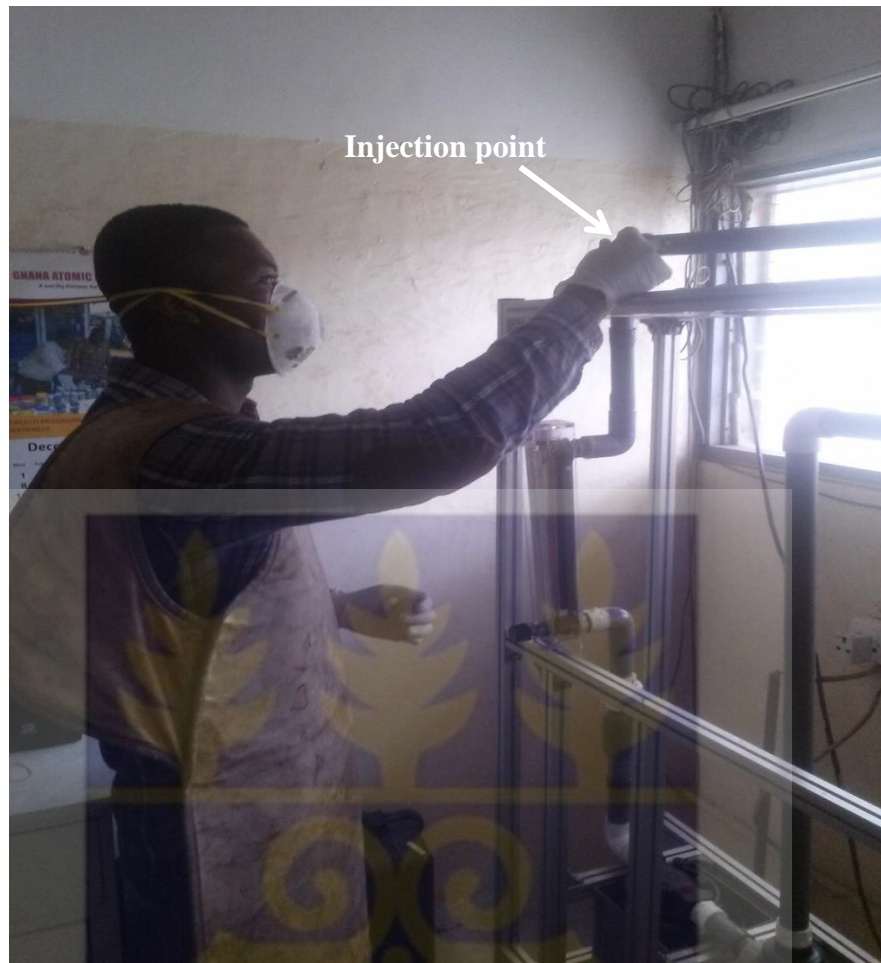


Figure 3.10: Injection of the tracer at the injection point

3.3.3 Tracer monitoring and Data acquisition

The concentration of a radiotracer in the exit stream of a system can be determined by two methods, the Sampling method and the On-line method[Chueinta ,2003.]. For this current study, the On-line method was used to monitor the radiotracer. Sodium iodide NaI(Tl) scintillation detectors(75x75 mm) were installed at the inlet of tank 1 and one each at the exit streams of each tank to monitor tracer concentration directly. Each detector in a lead shield was connected to a Ludlum model 16 analyzer (Data Acquisition System) set at a counting time of 30s. The counts per 30s registered by the analyzer were then recorded for data processing.

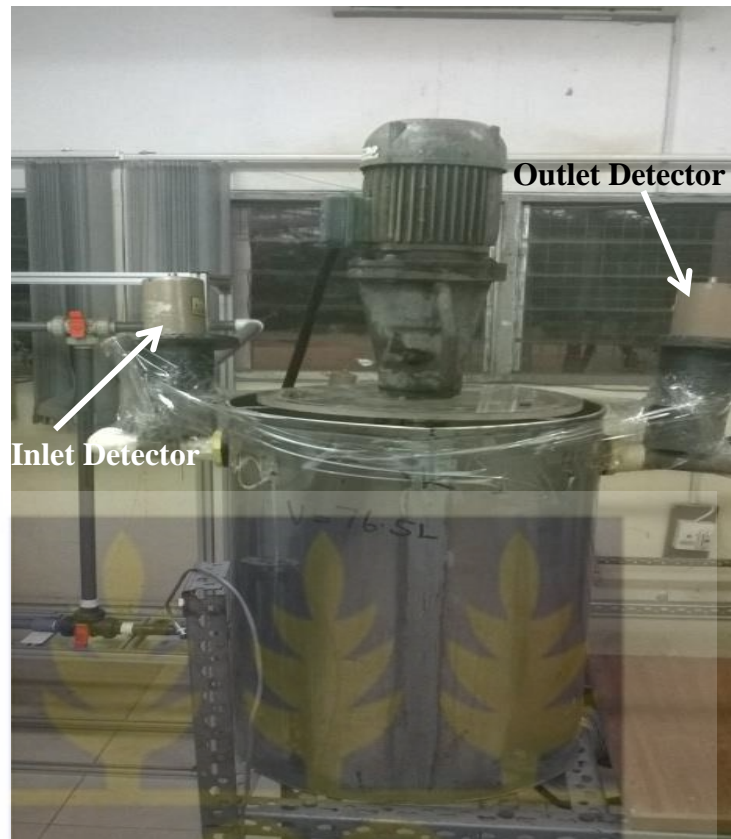


Figure 3.11: Detectors at inlet and exit of tank 1



Figure 3.12: Detector at exit of tank2



Figure 3.13: Detector at exit of tank 3



Figure 3.14: Detector at exit of tank 4

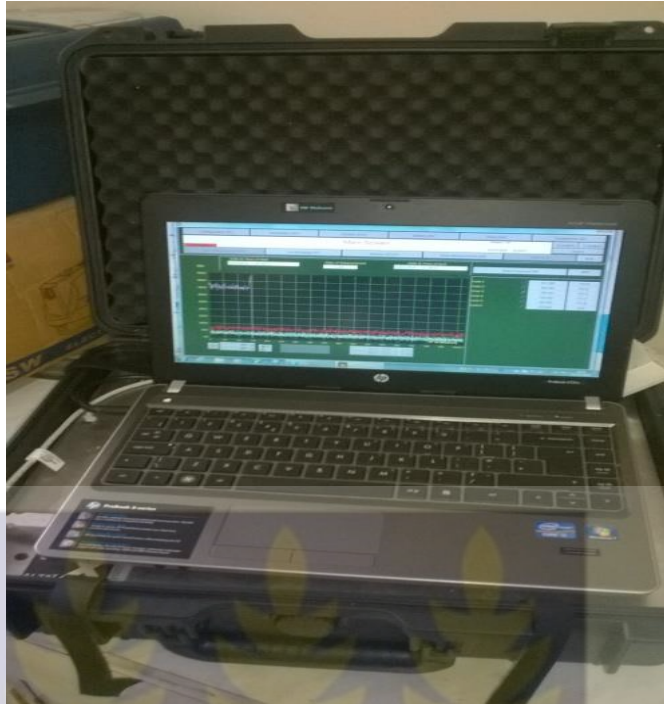


Figure 3.15: Data Acquisition System (DAS)

3.3.4. Procedure for the Radiotracer Experiment

By design, the maximum flow rate of water through the flow rig is 10 liters per minute. Therefore the 1000L water tank can supply water for a period of 1 hour 38minutes. For the current study, the flow rate was set at 10 liters per minute. Consequently, there were background counts for 5 minutes while the main experiment lasted for 40 minutes.

1. Ensured the water supply tank outside the laboratory was full and that the control valve V8 (Figure 3.1) is open.
2. Emptied the Waste water tank outside the laboratory and closed control valve V9 (Figure 3.1).
3. Ensured that all the detectors were in place.

Placed the Data Acquisition system (Figure 3.15) at the NDT laboratory and connected the channels as specified in the introduction

4. Started the water pump and run it for about 2min to make sure the flow was steady. Used V2 (Figure 3.1) to adjust the flow rate to 10L/min. This is to ensure that the stainless steel tanks did not overflow.
5. Started the agitators and run the system for 1min.
6. Prepared the DAS for background counts. Took background counts for 5min.
7. Prepared the DAS for the main experiment.
8. The tracer was injected and counting started (Figure 3.10).

3.4. Data processing

Prior to data analysis the experimental data was treated for background radiation that were at the experimental site. [IAEA, (2004).]. Thereafter, the data was treated for Tc-99 decay. Finally the experimental curve was normalized to obtain the distribution function $E(t)$

3.4.1 Background Radiation correction

The contribution of the background radiation to the data, due to industrial sources in the form of nuclear gauges, was eliminated [IAEA, (2001).]. In the current study, the correction was done by subtracting the contribution of the background (background radiation) from the experimental recorded data [ZHANG, 2003] according to the equation

$$C(t_i) = C_{exp}(t_i) - C_{bkg} \quad (2.3)$$

Where C_{bkg} = background count rate

C_{exp} = experimental count rate

3.4.2 Radioactive Decay correction

The experimental data from the DAS was treated for Tc-99 decay according to the equation

$$\begin{aligned} C(t_i) &= C_{exp}(t_i) \exp(\lambda t) \\ &= C_{exp}(t_i) \exp \frac{0.693t}{T_{1/2}} \end{aligned} \quad (2.4)$$

Where $C_{exp}(t_i)$ = the background corrected count rate

$C(t_i)$ = the decay corrected count rate

3.4.3 Area Normalization

Prior to data analysis, it was compulsory to convert the count rates into RTD functions represented by $E(t)$. The $E(t)$ function was obtained by dividing each data point under the $C(t)$ curve by the area. [PLASARI et al, 1999]

The $E(t)$ was estimated from the equation

$$E(t) = \frac{C(t)}{\int_0^{\infty} C(t) dt} \quad (2.5)$$

Such that

$$\int_0^{\infty} E(t) dt = 1 \quad (2.6)$$

3.5 Calculation of statistical parameters

The MRT and Variance were calculated from the method of moments. The method of moments was then used to numerically characterize the $E(t)$ functions in terms of statistical parameters. (Ham and Platzler, 2004; Santos and Dantas, 2004; Thyn et al., 2000; Naumann and Buffham, 1983;) According to this method, the zeroth moment of the distribution represents the area under the normalized tracer curve.

$$M_0 = \int_0^{\infty} E(t) dt = 1 \quad (2.6)$$

The value of the MRT, \bar{t} , was obtained from the first moment of the distribution curve.

$$M_1 = \int_0^{\infty} tE(t) dt = \bar{t} \quad (2.6.2)$$

$$\tau = V/Q \quad (3.1)$$

Equation (2.6.2) was used to calculate the cumulative residence times (CRT) of the tanks. The differences between consecutive CRTs obtained in the tanks represent the residence times of individual tanks and these values are listed in Table.4.1

The theoretical MRT for each tank was evaluated from Equation (3.1). It is worth mentioning here that the proper interpretation of RTD results partly depends on the value of the theoretical MRT which requires accurate measurement of V and Q . In this regard the volume of material in each tank was calculated, taking into

consideration the free board height (Fig. 3.15). During the investigation, the flow rate registered by the flow meters was 10L/min

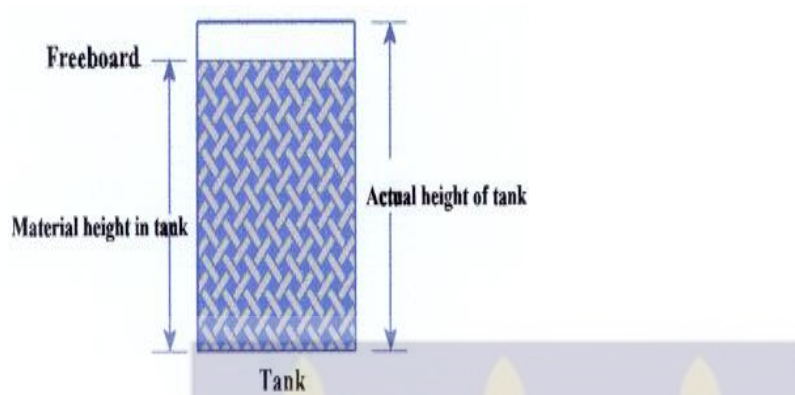


Figure 3. 1: shows measurement of free board height.

For a constant density fluid flowing in a system of volume V at flow rate Q , the theoretical MRT of the fluid (holding time) was calculated from equation 3.1

The variance which expresses the average squared distance of its possible values from the expected values (mean) [Lelinski et al (2002)] was evaluated from the equation:

$$\sigma^2 = \int_0^{\infty} (t - \bar{t})^2 E(t) dt \quad (2.6.1)$$

The fraction of dead space in the reactor was evaluated given by:

$$f_d = 1 - \frac{\bar{t}}{\tau} = 1 - \frac{V_{eff}}{V} \quad (3.2)$$

V_{eff} = effective volume of the reactor.

3.6 Modelling

To be able to define the flow structure of the studied systems, suitable mathematical models were used to simulate the experimentally obtained RTD data.

The criteria for selecting a suitable model are based on the shape of the experimental RTD curve, information obtained from the moments characterization of the $E(t)$ functions and flow structure of the investigated system. The parameters of the selected model were then adjusted to fit experimental values of the tracer concentration versus time curve. (IAEA, 2008; Boyer, 2002; Levenspiel, 1999)

Therefore considering the serial arrangement of the stirred tanks, the experimental curve is expected to fit perfect-mixers- in- series model. The experimental response curves were simulated with the following models using the RTD analysis software DTSPRO 4.21. The first simulation was the perfect mixers in series model, followed by the perfect mixers in series with exchange model, then finally the perfect mixers in series with back-mixing model.



CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

This section of the work focuses on the results obtained from both the experimental data and simulations. The results from tank 1(one axial flow impeller), tank 2(two axial flow impellers), tank 3 (two radial flow impellers) and tank 4 (no stirrers) have been considered in the current discussion.

4.2. Results

To determine the effect of the radial or axial flow impeller on the MRT of the various tanks, the MRT of the four tanks was calculated from the experimental data using the method of moments. Plots of the RTD curves [$E(t)$ versus sampling time (t)] for each tank followed the normal exponential decay curves typical of ideal mixers (figures 4.1,4.2,4.3,4.4). However, the curves exhibited long tail indicating deviation from ideality. The very sharp peak exhibited by fig.4.1 indicated initial high concentration and the almost instantaneous injection of the tracer and the subsequent decay as the tracer passes in the next tank. Moreover the shape of the curve in fig.4.4 suggests existence of short circuiting in the tank [Jean-Pierre et al, 2007].

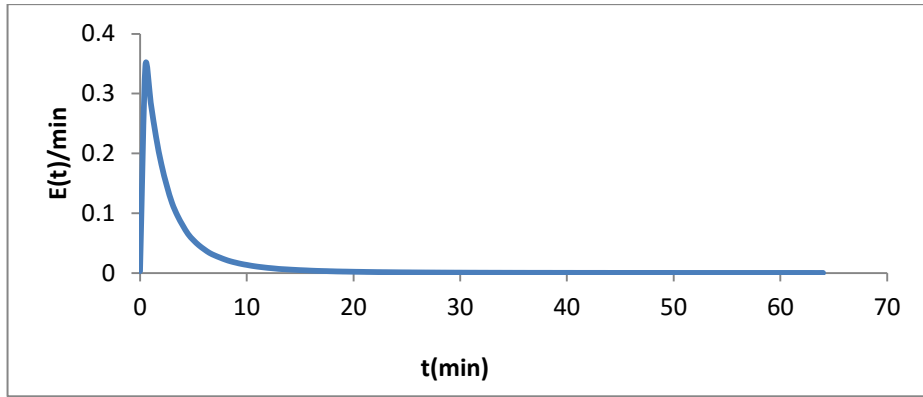


Figure 4. 1: $E(t)$ experimental data curve for tank 1

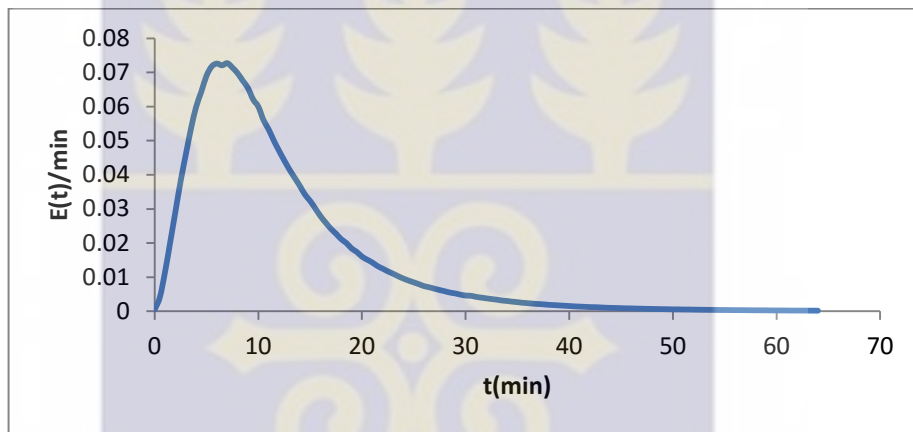


Figure 4. 2: experimental $E(t)$ data curve for tank 2



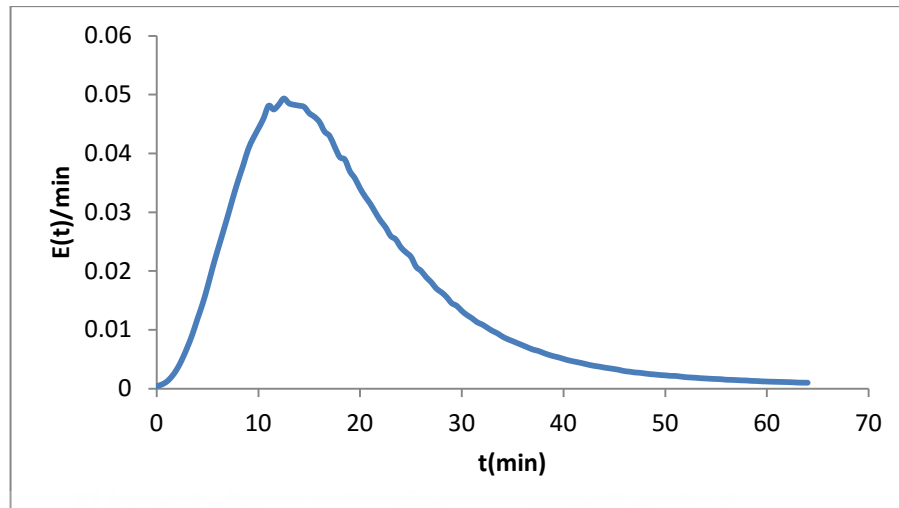


Figure 4. 3: Experimental E(t) data curve for tank 3

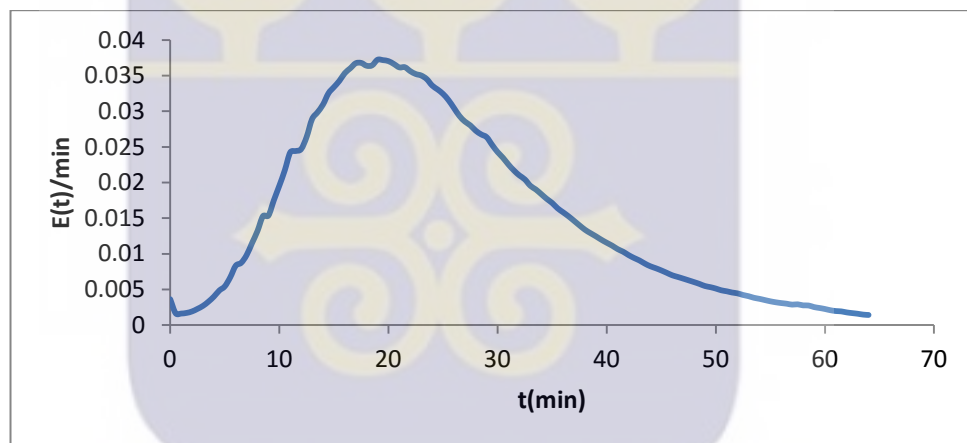


Figure 4. 4: Experimental E(t) data curve for tank 4

The method of moments was then used to numerically characterize the E(t) functions in terms of statistical parameters by the application of Microsoft excel and DTSPRO V4.2 software in order to minimise errors. (Ham and Platzer, 2004; Santos and Dantas, 2004; Thyn et al., 2000; Naumann and Buffham, 1983;). According to this method, the zeroth moment of the distribution represents the area under the normalized tracer curve and the first moment represents the MRT. The results from the method of moments is shown in the table 4.1

4.3. Summary of Results from Method of Moments

Table 4. 1: Results from the method of moments

PARAMETERS	TANK 1(one axial flow impeller)	TANK 2(two axial flow impellers)	TANK 3(two radial flow impellers)	TANK4(no stirrers)
Active capacity [L]	66.2	66.2	66.2	66.2
Theoretical MRT (τ)	6.6	6.6	6.6	6.6
Experimental cumulative MRT (\bar{t})	5.3	12.8	19.9	25.1
Experimental MRT per tank, (\bar{t})	5.3	7.5	7.1	5.1
Variance	$1.5 \cdot 10^5$	$1.8 \cdot 10^5$	$1.7 \cdot 10^5$	$0.7 \cdot 10^5$
% dead space	19.6	–	–	22.7
%effective volume	80.4	–	–	77.3

The value of the experimental MRT compared with the expected (nominal) MRT is a very important deterministic factor of the performance of all industrial reactors.

For a constant density fluid flowing in a system of volume V at flow rate $Q(10L/min)$, the MRT of the fluid (holding time) is theoretically defined as the ratio of the system volume to the flow rate

If a system operates without flow abnormalities, then the measured experimental MRT (\bar{t}) is the same as the holding time. However, if $\bar{t} < \tau$, as observed in tank 1 (one radial flow impeller), where the experimental MRT (\bar{t}) was measured as 5.3 as against 6.6 for the theoretical MRT (τ) and in tank 4 where the \bar{t} was measured as 5.1 and the τ as 6.6. It indicates that if the mean of the distribution arrives too early, then there is possibility of fouling/scaling in the reactor (Pant et al, 2002). This implies the one axial flow impeller in tank 1 produces axial flow patterns which results in reduction in the material volume of the reactor signifying the presence of dead space in the system. The percentage dead space was estimated to be less than 20% with effective tank volume to be 80% which is normal. The dead space in tank 4 (no stirrers) was estimated to be more than 20% but it's not entirely dead space because the shape of its $E(t)$ curve suggests there is short circuiting. The observation in tank 4 was however expected due to the fact that there were no stirrers in the tank. In a situation where $\bar{t} > \tau$ as in the case of tank 2 where its \bar{t} measured as 7.5 as against 6.7 for τ and tank 3 whose \bar{t} was measured as 7.1 as against 6.5 for τ it follows that: The holding time might be wrongly calculated due to errors in flow rate measurement or volume calculation. It can also be that the tracer used is not inert, it is adsorbed on the walls of the vessel. The tanks exchange its contents with the main flow which suggests there is severe stagnancy. This situation however can only be confirmed from the shape of the experimental curve and subsequent modelling of the

data. It is observed that the MRTs obtained during the investigation, for tanks 2 and 3 exceed the calculated theoretical MRT. The implication is that the tracer resides in those tanks longer than expected, and in the case of tanks 1 and 4, the tracer resides in the tanks shorter than expected. The reasons can be known through mathematical modeling of the experimental data.

Determination of which impeller type gave the best mixing was deduced from the variance of the tanks containing the various impeller configurations, better mixing tends to give a higher mean residence time of the studied system by Aguado et al, 2012. According to Hassanzadeh et al, 2015, The variance reflects the degree of mixing within the vessel, in that the greater the variance, the better the degree of mixing. Considering the experimental mean residence times (MRT) and the variance of the various tanks and comparing them, it can be seen that in terms of both higher MRT and variance, the tanks can be ranked as tank 4 < tank 1 < tank 3 < tank 2. This means that tank 2 with two axial flow impellers has the best mixing, followed by tank 3 which has two radial flow impellers, then tank 1 with one axial flow impeller, then finally tank 4 with no impellers. Furthermore, it can be said that two axial flow impellers (tank 2) produce better mixing than one axial flow impeller (tank 1)

4.4. Modelling of Experimental RTD

To be able to describe the flow structure of the studied systems, suitable mathematical models were used to simulate the experimentally obtained RTD data using the DTSPRO V4.2 software produced by PROGERI, France (2000). The criteria for selecting a suitable model was based on the shape of the experimental RTD curve, information obtained from the moments characterization of the $E(t)$

functions and flow structure of the investigated system. The parameters of the selected model were then adjusted to fit experimental values of the tracer concentration versus time curve. (IAEA, 2008; Boyer, 2002 and Levenspiel, 1999). Considering the serial arrangement of the studied tanks, the experimental curve was expected to either fit with the perfect-mixers- in- series model, perfect mixers in series with exchange model or perfect mixers in series with backmixing model for tanks 1,2 and 3 and 4. However, attempts to fit the first two models with the measured data resulted in poor agreement between measured and predicted retention time distribution curves. The results from the curve fittings for perfect mixers in series is shown in Figs.4.5 -4.8 and that of perfect mixers in series with exchange is shown in Figs.4.9- 4.12

The experimental data was simulated with the perfect mixers in series with back-mixing using the DTSPRO V4.2 software produced by PROGERI, France (2000). The model fitted very well with the measured data and predicted flow of the tracer in the tanks more accurately. This model takes into account the backflow of the studied process. The model has three parameters; the mean residence time, number of mixing cells: J and back flow rate ratio: α .

The fits are shown in Figs. 4.13-4.16 and The corresponding model parameters including the total MRT calculated from Eqn. (2.6.2) are given in Table.4.1. The calculated model MRTs are agree with the cumulative MRTs obtained from the method of moments.

Therefore, the unusual long tails exhibited by the retention curves indicated the existence of back mixing in the tanks. The back flow is at slow rate and causes the long tails in the experimental RTD curve resulting in longer MRTs in tanks 2 and 3.

4.5. Modelling Results for Perfect Mixers in Series

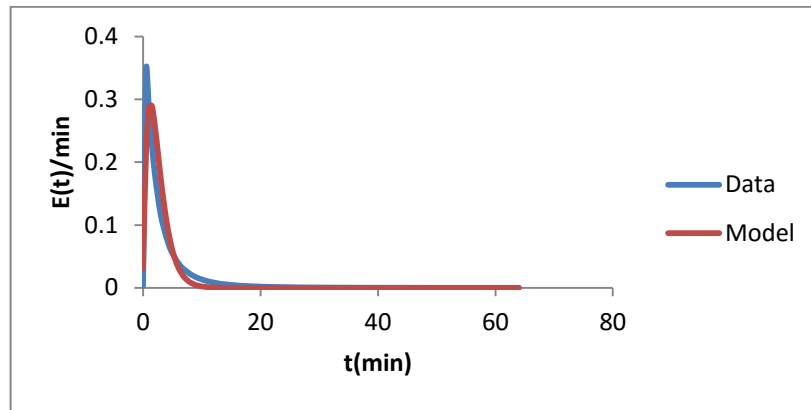


Figure 4. 5: Simulated curve of Perfect mixer in series model (Tank1)

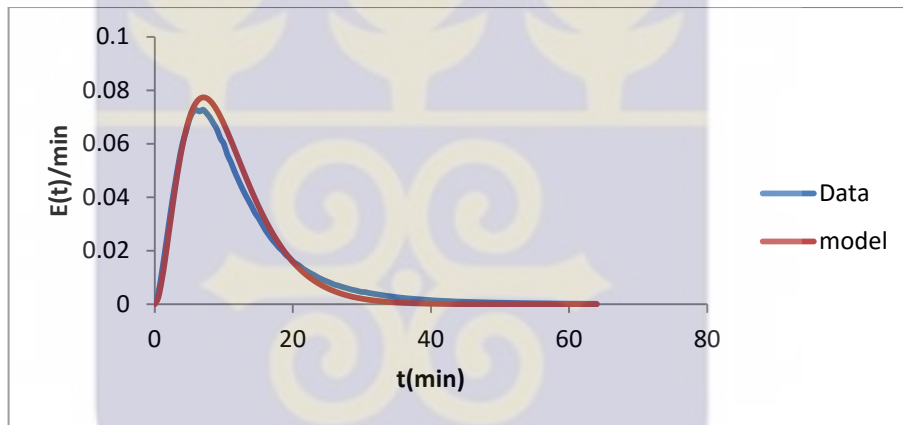


Figure 4. 6: Simulated curve of Perfect mixer in series model (Tank2)

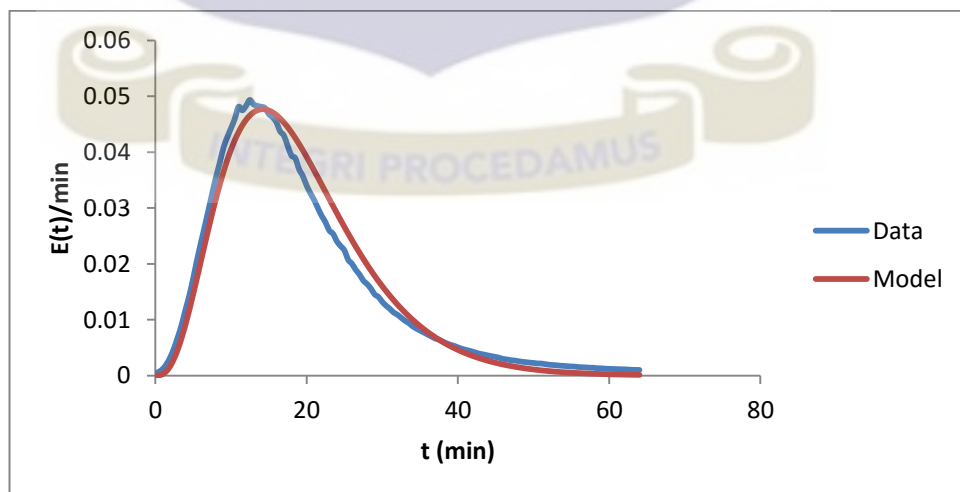


Figure 4. 7: Simulated curve of Perfect mixer in series model (Tank 3)

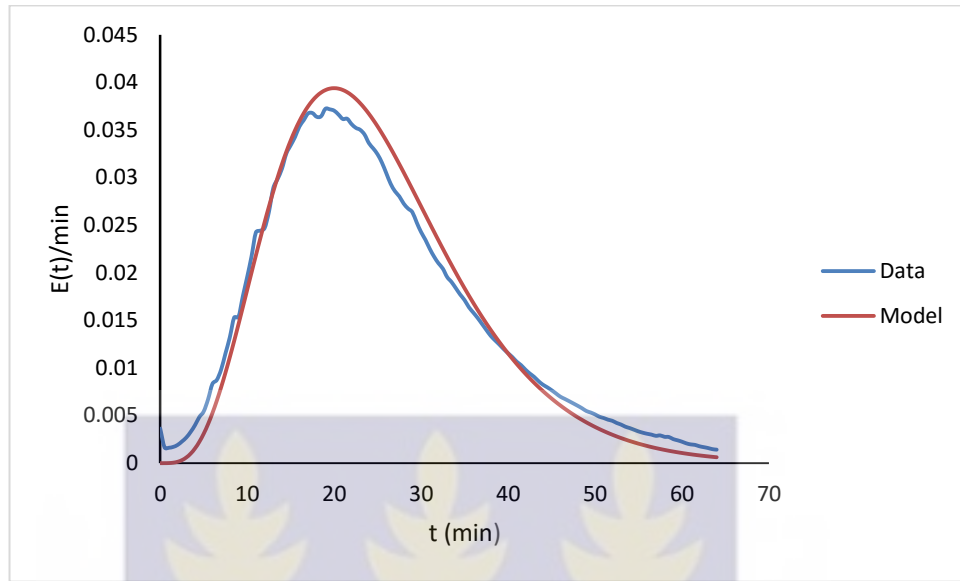


Figure 4. 8: Simulated curve of Perfect mixer in series model (Tank 4)

4.6. Simulation Parameters for Perfect Mixers in Series

Table 4. 2 Simulation parameters for perfect mixers in series

Parameters	Tank 1	Tank 2	Tank 3	Tank4
Mean residence time (τ)	2.5	10.5	18.8	24.8
Number of mixing cells (J)	2	3	4	5

4.7. Model Results for Perfect Mixer in Series with Exchange

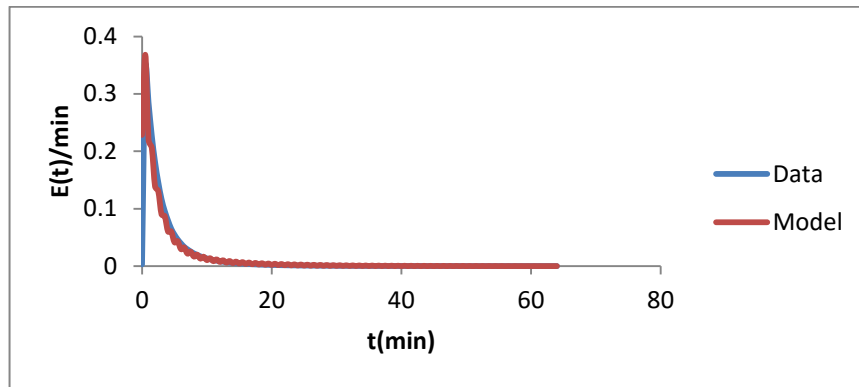


Figure 4. 9: Simulated curve of Perfect mixer in series with exchange model (Tank 1)

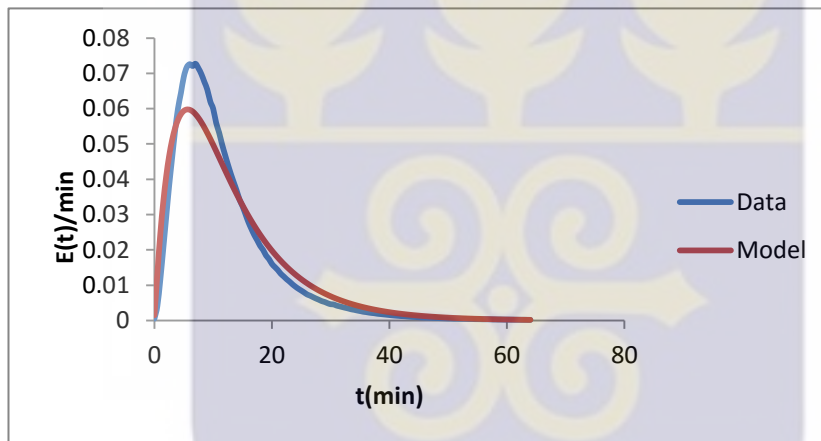


Figure 4.10: Simulated curve of Perfect mixer in series with exchange model (Tank 2)

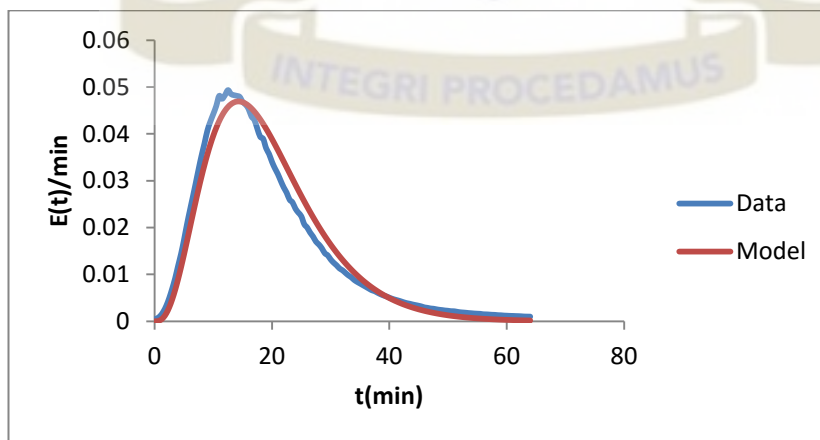


Figure 4. 11: Simulated curve of Perfect mixer in series with exchange model (Tank 3)

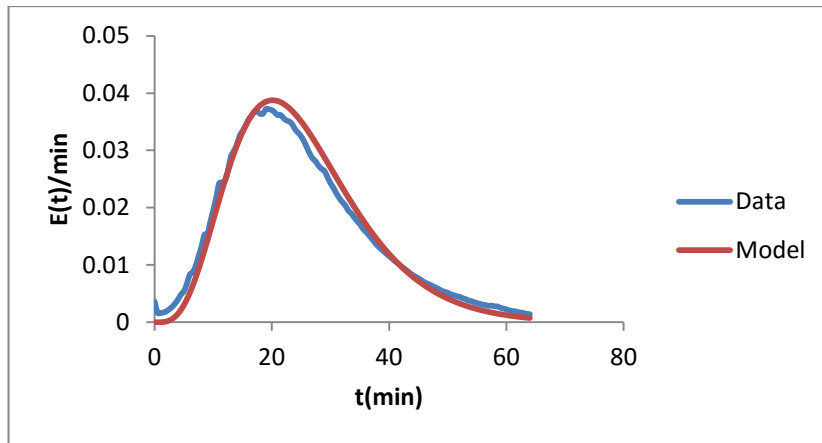


Figure 4. 12: Simulated curve of Perfect mixer in series with exchange model (Tank 4)

4.8. Model Parameters

Table 4. 3: Simulation parameters for perfect mixers in series with exchange

Parameters	Tank 1(one axial impeller)	Tank 2(two axial impellers)	Tan3 (two radial impellers)	Tank4(no stirrers)
MRT of active volume(t_{act})	5.1	11.6	18.9	24.9
Exchange time constant(t_m)	6.6	6.8	6.9	7
Numberof mixing cell(J)	0.9	2	4	4.5
Volume ratio (K)	0.5	0.1	0.01	0.01

4.9. Results for the Perfect Mixers in Series with Back-Mixing

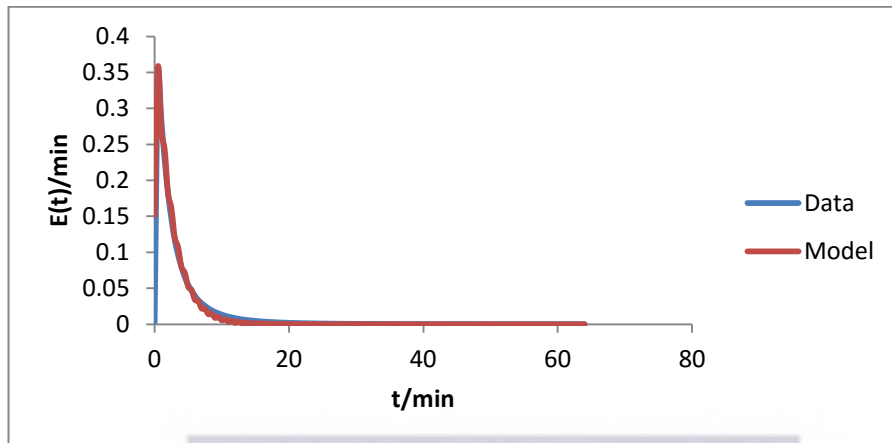


Figure 4. 13: Simulated $E(t)$ model fit curve of Perfect mixer in series with back-mixing model (Tank 1)

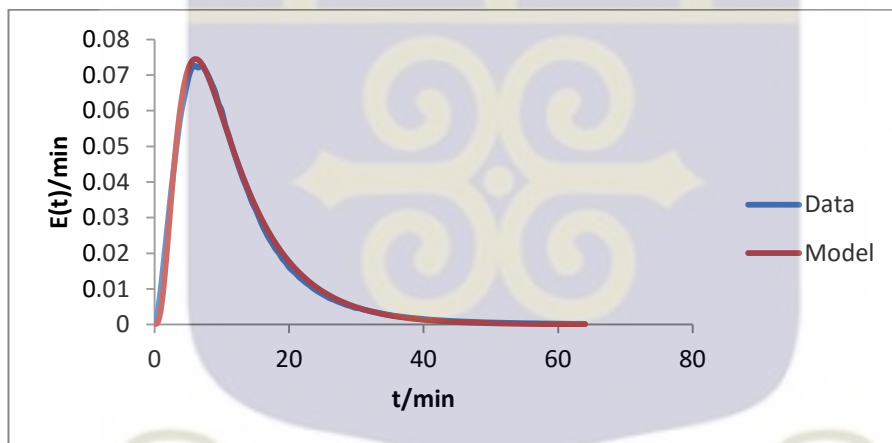


Figure 4. 14: Simulated $E(t)$ model fit curves of Perfect mixer in series with back-mixing model (Tank 2)

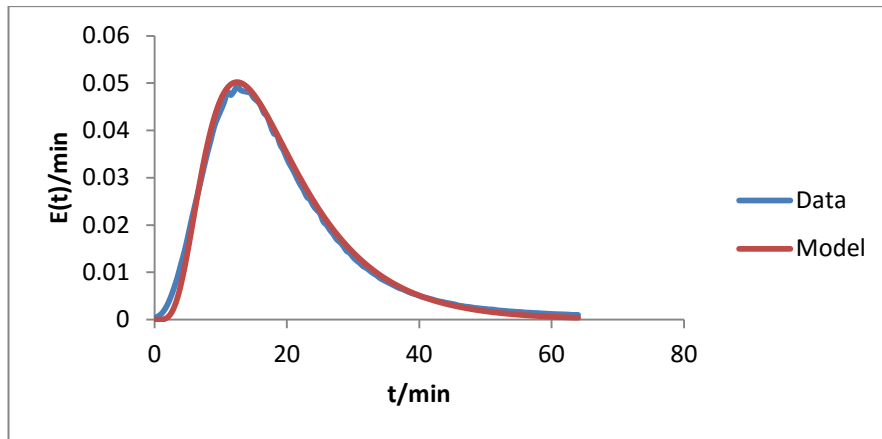


Figure 4. 15: Simulated E(t) model fit curves of Perfect mixer in series with back-mixing model (Tank 3)

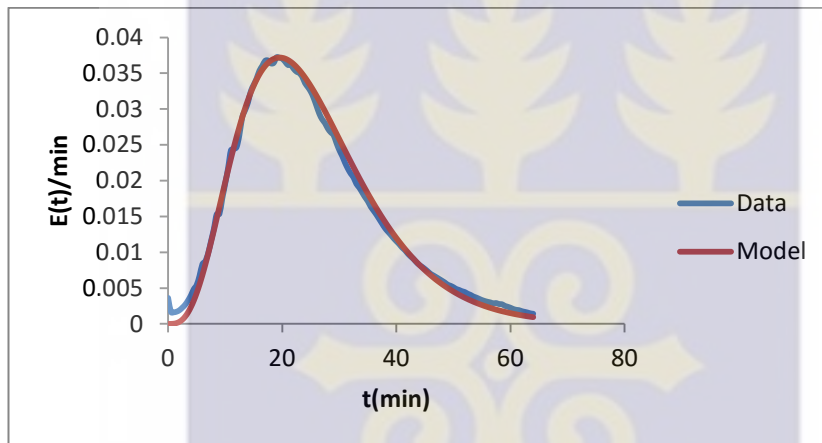


Figure 4. 16: Simulated E(t) model fit curves of Perfect mixer in series with back-mixing model(Tank 4)



Table 4.4: Simulation parameters of perfect mixers in series with back-mixing model

Model	Tank 1(one axial flow impeller)	Tank 2(two axial flow impellers)	Tank 3(two radial flow impellers)	Tank 4(no stirrers)
Mean residence time (τ)	2.5	11.7	18.9	26.7
Number of mixing cell (J)	1.2	4.5	7.0	8.9
Back flow-rate ratio (α)	1.0	1.0	0.8	0.9



CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The residence time distribution of the four tanks containing the different flow impeller configurations was obtained from the radiotracer experiment. Though the residence time distribution measured at the outlet of the tanks decrease exponentially as in the case of perfect mixers they deviated from ideality due to the long tails exhibited towards the end of the curves. The experimental mean residence times (MRT) evaluated from the method of moments for the two axial flow impellers and the two radial flow impeller tanks clearly exceeded the theoretical mean residence times calculated with respect to the volume and flow rate. The two axial flow impellers was the highest. The conclusion is that the tracer resides in those tanks longer than expected. However the experimental MRT of the one axial flow impeller tank and the tank 4 with no stirrers was lower than the theoretical MRT. There is presence of dead volume in both tanks implying that the vessels are working normally with effective volumes of 80.4% and 77.3% shown in Table 4.1 for tanks 1 and tank 4 respectively. The relatively low effective volume of the tank 4(no stirrers) is as a result of short circuiting.

The effect of the different flow impeller configurations on mixing was achieved by calculation of the variance from the method of moments. Higher variance implies better mixing. Therefore comparing the variances, the two axial flow impellers gives better mixing than the two radial flow impellers. Between the two and the one axial flow impellers, the two impellers gave a better mixing. It can be concluded that two

axial flow impellers should be the preferred choice for industrial purposes to achieve better mixing.

The determination of the flow structure in the various tanks with different flow impeller configurations, was achieved by simulating the experimental RTD curves with three different flow models using the RTD data analysis software DTSPRO V4.2 produced by PROGERI, 2000. The perfect mixers in series with back-mixing model gave the best fit and described the flow structure in the tanks.

5.2 Recommendations

The following are some suggestions which need to be carried out in the future.

1. Further studies on the impellers should be conducted by controlling the speed of the stirrers since some of the tanks in the current study experienced water being plashed from it.
2. Further studies should be conducted to determine which flow model best describes the flow structure in stirred vessels with various flow impeller configurations, since some suggest the perfect mixers in series with exchange is the best.

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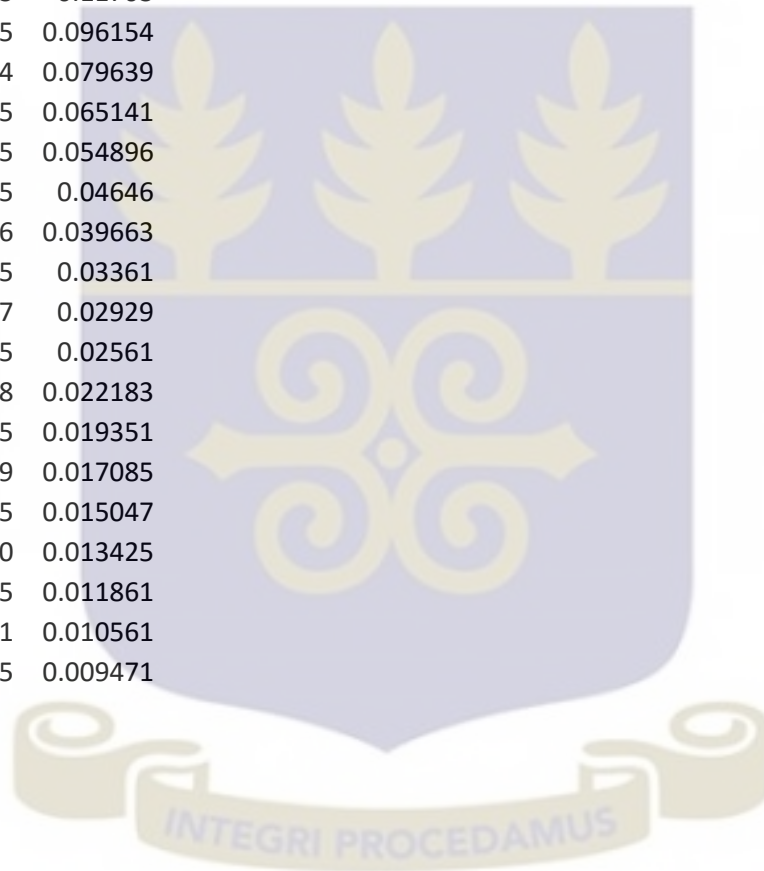
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APPENDICES

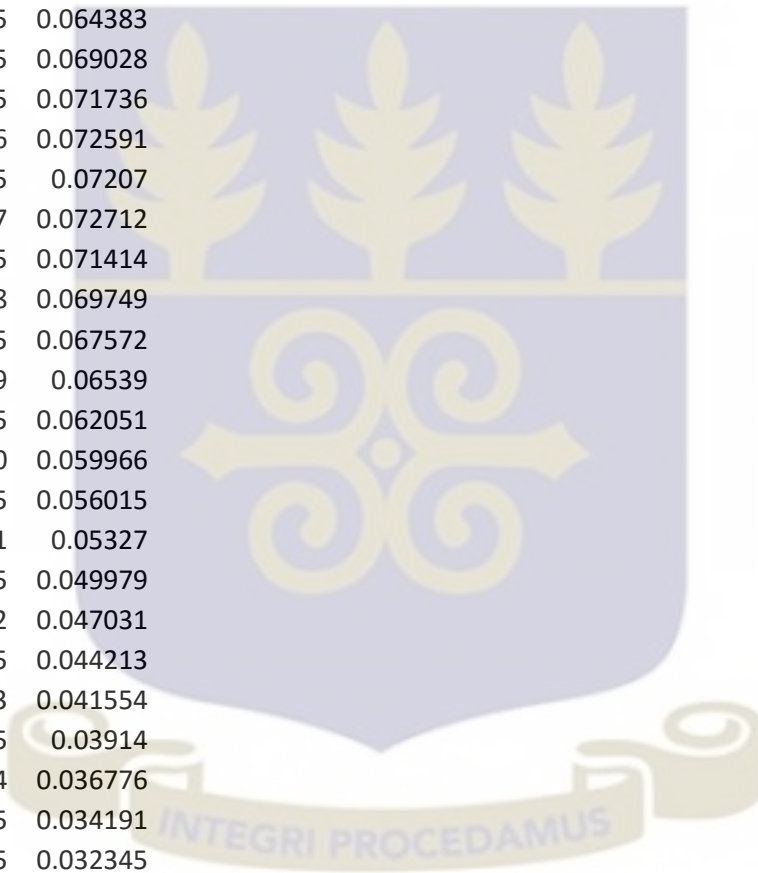
Appendix A: NORMALISED DATA TANK1 TO TANK4

time	Data
0	0.00294
0.5	0.34537
1	0.28505
1.5	0.22765
2	0.1819
2.5	0.14648
3	0.11703
3.5	0.096154
4	0.079639
4.5	0.065141
5	0.054896
5.5	0.04646
6	0.039663
6.5	0.03361
7	0.02929
7.5	0.02561
8	0.022183
8.5	0.019351
9	0.017085
9.5	0.015047
10	0.013425
10.5	0.011861
11	0.010561
11.5	0.009471



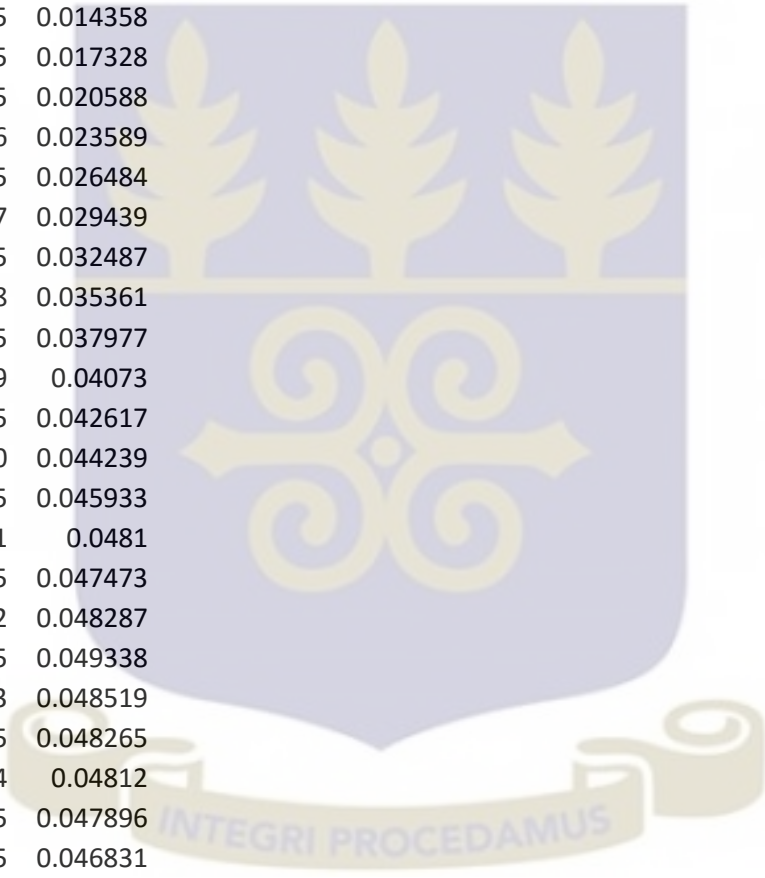
NORMALISED DATA FOR TANK 2

Time	Data
0	0.000526
0.5	0.004146
1	0.011579
1.5	0.020301
2	0.029236
2.5	0.038126
3	0.045914
3.5	0.053519
4	0.059933
4.5	0.064383
5	0.069028
5.5	0.071736
6	0.072591
6.5	0.07207
7	0.072712
7.5	0.071414
8	0.069749
8.5	0.067572
9	0.06539
9.5	0.062051
10	0.059966
10.5	0.056015
11	0.05327
11.5	0.049979
12	0.047031
12.5	0.044213
13	0.041554
13.5	0.03914
14	0.036776
14.5	0.034191
15	0.032345
15.5	0.030115



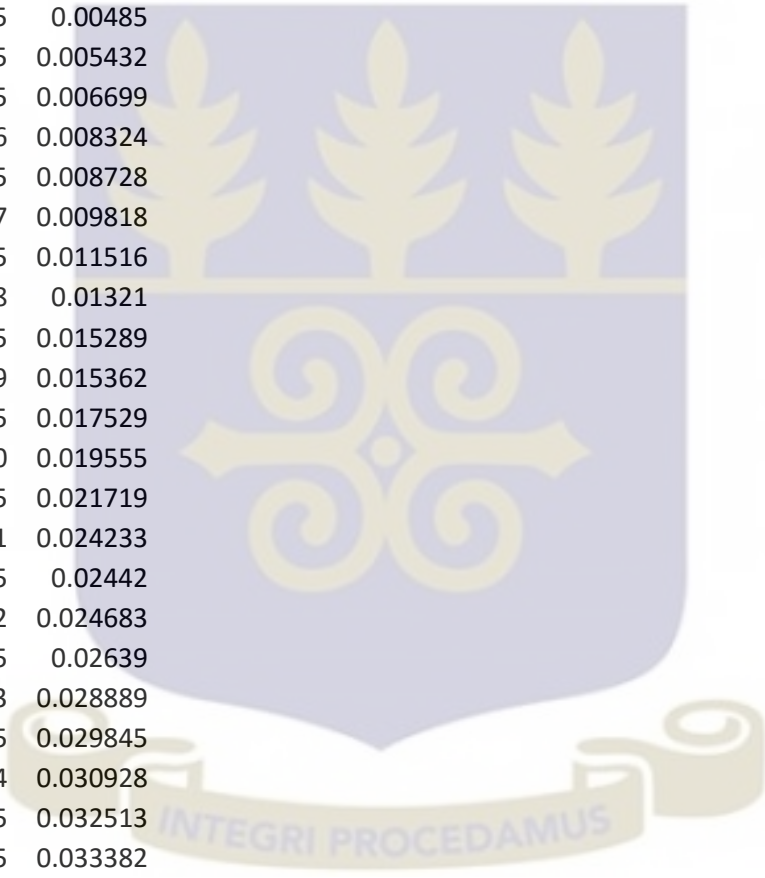
NORMALISED DATA FOR TANK 3

time	Data
0	0.000418
0.5	0.000691
1	0.001199
1.5	0.002089
2	0.003337
2.5	0.004992
3	0.00698
3.5	0.009183
4	0.011824
4.5	0.014358
5	0.017328
5.5	0.020588
6	0.023589
6.5	0.026484
7	0.029439
7.5	0.032487
8	0.035361
8.5	0.037977
9	0.04073
9.5	0.042617
10	0.044239
10.5	0.045933
11	0.0481
11.5	0.047473
12	0.048287
12.5	0.049338
13	0.048519
13.5	0.048265
14	0.04812
14.5	0.047896
15	0.046831
15.5	0.046234



NORMALISED DATA FOR TANK 4

time	Data
0	0.003631
0.5	0.001649
1	0.00162
1.5	0.001708
2	0.001916
2.5	0.002278
3	0.002695
3.5	0.003283
4	0.003992
4.5	0.00485
5	0.005432
5.5	0.006699
6	0.008324
6.5	0.008728
7	0.009818
7.5	0.011516
8	0.01321
8.5	0.015289
9	0.015362
9.5	0.017529
10	0.019555
10.5	0.021719
11	0.024233
11.5	0.02442
12	0.024683
12.5	0.02639
13	0.028889
13.5	0.029845
14	0.030928
14.5	0.032513
15	0.033382
15.5	0.034252
16	0.035344
16.5	0.036018
17	0.036727
17.5	0.036775
18	0.036378
18.5	0.036433



Appendix B: Normalized PMS Simulation Data

time	Data	pms T1
0	0.00294	0.031666
0.5	0.34537	0.21142
1	0.28505	0.28732
1.5	0.22765	0.28974
2	0.1819	0.25939
2.5	0.14648	0.21847
3	0.11703	0.17583
3.5	0.096154	0.13835
4	0.079639	0.10593
4.5	0.065141	0.080493
5	0.054896	0.059799
5.5	0.04646	0.044545
6	0.039663	0.032381
6.5	0.03361	0.023862
7	0.02929	0.017021
7.5	0.02561	0.012506
8	0.022183	0.00874
8.5	0.019351	0.006461
9	0.017085	0.004394
9.5	0.015047	0.003315
10	0.013425	0.002159
10.5	0.011861	0.001703
11	0.010561	0.001029
11.5	0.009471	0.000887
12	0.008463	0.000465
12.5	0.007652	0.000477
13	0.006763	0.000188
13.5	0.006219	0.000271
14	0.005676	5.45E-05
14.5	0.005181	0.000168
15	0.004684	-8.60E-06
15.5	0.004347	0.000115
16	0.003896	-3.72E-05
16.5	0.003561	8.75E-05
17	0.003257	-4.91E-05
17.5	0.003058	7.23E-05
18	0.00276	-5.31E-05
18.5	0.002531	6.33E-05

Normalized PMS Simulation Data for Tank 2

time	Data	model
0	0.000526	8.30E-06
0.5	0.004146	0.002454
1	0.011579	0.008673
1.5	0.020301	0.016867
2	0.029236	0.026065
2.5	0.038126	0.035313
3	0.045914	0.044155
3.5	0.053519	0.052137
4	0.059933	0.059114
4.5	0.064383	0.064914
5	0.069028	0.069562
5.5	0.071736	0.073035
6	0.072591	0.07544
6.5	0.07207	0.076827
7	0.072712	0.077334
7.5	0.071414	0.077035
8	0.069749	0.076073
8.5	0.067572	0.074522
9	0.06539	0.072512
9.5	0.062051	0.070109
10	0.059966	0.067422
10.5	0.056015	0.064503
11	0.05327	0.061442
11.5	0.049979	0.058274
12	0.047031	0.055071
12.5	0.044213	0.051854
13	0.041554	0.048677
13.5	0.03914	0.045552
14	0.036776	0.042518
14.5	0.034191	0.039577
15	0.032345	0.03676
15.5	0.030115	0.034061
16	0.027862	0.0315
16.5	0.025965	0.029069
17	0.024198	0.026783
17.5	0.022718	0.024627
18	0.021132	0.022614
18.5	0.019982	0.020728

Normalized PMS Simulation Data for Tank 3

		-8.57E-
0	0.000418	07
0.5	0.000691	3.78E-05
1	0.001199	0.00027
1.5	0.002089	0.000821
2	0.003337	0.00175
2.5	0.004992	0.003076
3	0.00698	0.004782
3.5	0.009183	0.006833
4	0.011824	0.009178
4.5	0.014358	0.011759
5	0.017328	0.014514
5.5	0.020588	0.017383
6	0.023589	0.020307
6.5	0.026484	0.023232
7	0.029439	0.02611
7.5	0.032487	0.028897
8	0.035361	0.031557
8.5	0.037977	0.034059
9	0.04073	0.03638
9.5	0.042617	0.0385
10	0.044239	0.040406
10.5	0.045933	0.04209
11	0.0481	0.043545
11.5	0.047473	0.044773
12	0.048287	0.045774
12.5	0.049338	0.046555
13	0.048519	0.047122
13.5	0.048265	0.047484
14	0.04812	0.047653
14.5	0.047896	0.047639
15	0.046831	0.047456
15.5	0.046234	0.047116
16	0.045351	0.046633
16.5	0.043721	0.046019
17	0.042965	0.045289
17.5	0.041113	0.044454
18	0.039368	0.043528
18.5	0.038941	0.042523
19	0.036936	0.041451
19.5	0.035722	0.040321

Normalized PMS Simulation Data for Tank 4

0	0.003631	1.68E-08
0.5	0.001649	7.85E-07
1	0.00162	1.10E-05
1.5	0.001708	5.05E-05
2	0.001916	0.000144
2.5	0.002278	0.000319
3	0.002695	0.000598
3.5	0.003283	0.001002
4	0.003992	0.001547
4.5	0.00485	0.002243
5	0.005432	0.003093
5.5	0.006699	0.004097
6	0.008324	0.00525
6.5	0.008728	0.006543
7	0.009818	0.007963
7.5	0.011516	0.009495
8	0.01321	0.011122
8.5	0.015289	0.012825
9	0.015362	0.014585
9.5	0.017529	0.016383
10	0.019555	0.018199
10.5	0.021719	0.020016
11	0.024233	0.021815
11.5	0.02442	0.023579
12	0.024683	0.025294
12.5	0.02639	0.026946
13	0.028889	0.028523
13.5	0.029845	0.030013
14	0.030928	0.031408
14.5	0.032513	0.032701
15	0.033382	0.033886
15.5	0.034252	0.034957
16	0.035344	0.035913
16.5	0.036018	0.036751
17	0.036727	0.03747
17.5	0.036775	0.038072
18	0.036378	0.038557
18.5	0.036433	0.038928

Appendix C: Normalized and PMSE Simulation Data

TANK 1

Time	Data	Model
0	0.00294	0.22848
0.5	0.34537	0.36817
1	0.28505	0.22023
1.5	0.22765	0.20629
2	0.1819	0.13909
2.5	0.14648	0.13074
3	0.11703	0.09025
3.5	0.096154	0.087078
4	0.079639	0.060266
4.5	0.065141	0.060357
5	0.054896	0.041495
5.5	0.04646	0.043457
6	0.039663	0.029518
6.5	0.03361	0.032469
7	0.02929	0.021714
7.5	0.02561	0.025125
8	0.022183	0.016505
8.5	0.019351	0.020068
9	0.017085	0.01293
9.5	0.015047	0.016472
10	0.013425	0.010398
10.5	0.011861	0.013827
11	0.010561	0.008544
11.5	0.009471	0.011817
12	0.008463	0.00714
12.5	0.007652	0.010239
13	0.006763	0.006042
13.5	0.006219	0.008966
14	0.005676	0.005159
14.5	0.005181	0.007915
15	0.004684	0.004432
15.5	0.004347	0.007028
16	0.003896	0.003821
16.5	0.003561	0.00627
17	0.003257	0.003301
17.5	0.003058	0.005613
18	0.00276	0.002853
18.5	0.002531	0.00504

Normalized and PMSE Simulation Data for Tank 2

Time	Data	PMSE T2
0	0.000526	0.001493
0.5	0.004146	0.013285
1	0.011579	0.024565
1.5	0.020301	0.033522
2	0.029236	0.040823
2.5	0.038126	0.046562
3	0.045914	0.051035
3.5	0.053519	0.054387
4	0.059933	0.056808
4.5	0.064383	0.058428
5	0.069028	0.059378
5.5	0.071736	0.059763
6	0.072591	0.059677
6.5	0.07207	0.059202
7	0.072712	0.058406
7.5	0.071414	0.057353
8	0.069749	0.056089
8.5	0.067572	0.054663
9	0.06539	0.05311
9.5	0.062051	0.051465
10	0.059966	0.049751
10.5	0.056015	0.047997
11	0.05327	0.046217
11.5	0.049979	0.044432
12	0.047031	0.042651
12.5	0.044213	0.04089
13	0.041554	0.039153
13.5	0.03914	0.037453
14	0.036776	0.03579
14.5	0.034191	0.034173
15	0.032345	0.032603
15.5	0.030115	0.031084
16	0.027862	0.029616
16.5	0.025965	0.028203
17	0.024198	0.026842
17.5	0.022718	0.025537
18	0.021132	0.024283
18.5	0.019982	0.023084

Normalized and PMSE Simulation Data for Tank 3

time	Data	PMSE T3
0	0.000418	-8.24E-07
0.5	0.000691	3.71E-05
1	0.001199	0.000264
1.5	0.002089	0.000803
2	0.003337	0.001712
2.5	0.004992	0.003009
3	0.00698	0.004679
3.5	0.009183	0.006686
4	0.011824	0.00898
4.5	0.014358	0.011506
5	0.017328	0.014202
5.5	0.020588	0.017011
6	0.023589	0.019874
6.5	0.026484	0.02274
7	0.029439	0.02556
7.5	0.032487	0.028294
8	0.035361	0.030905
8.5	0.037977	0.033363
9	0.04073	0.035646
9.5	0.042617	0.037734
10	0.044239	0.039615
10.5	0.045933	0.041279
11	0.0481	0.042723
11.5	0.047473	0.043945
12	0.048287	0.044948
12.5	0.049338	0.045736
13	0.048519	0.046316
13.5	0.048265	0.046697
14	0.04812	0.046889
14.5	0.047896	0.046904
15	0.046831	0.046753
15.5	0.046234	0.046449
16	0.045351	0.046005
16.5	0.043721	0.045433
17	0.042965	0.044746
17.5	0.041113	0.043958
18	0.039368	0.043079
18.5	0.038941	0.042121

Normalized and PMSE Simulation Data for Tank 4

time	Data	PMSE T4
0	0.003631	1.06E-07
0.5	0.001649	8.53E-07
1	0.00162	1.09E-05
1.5	0.001708	4.95E-05
2	0.001916	0.000141
2.5	0.002278	0.000312
3	0.002695	0.000585
3.5	0.003283	0.000981
4	0.003992	0.001514
4.5	0.00485	0.002194
5	0.005432	0.003025
5.5	0.006699	0.004006
6	0.008324	0.005133
6.5	0.008728	0.006397
7	0.009818	0.007785
7.5	0.011516	0.009282
8	0.01321	0.010872
8.5	0.015289	0.012537
9	0.015362	0.014257
9.5	0.017529	0.016016
10	0.019555	0.017793
10.5	0.021719	0.01957
11	0.024233	0.021331
11.5	0.02442	0.023059
12	0.024683	0.02474
12.5	0.02639	0.026361
13	0.028889	0.027908
13.5	0.029845	0.029373
14	0.030928	0.030746
14.5	0.032513	0.032021
15	0.033382	0.03319
15.5	0.034252	0.034251
16	0.035344	0.035199
16.5	0.036018	0.036033
17	0.036727	0.036753
17.5	0.036775	0.037359
18	0.036378	0.037851
18.5	0.036433	0.038233

Appendix D: Normalized and PMSB Simulation Data

TANK 1

time	Data	PMSB T1
0	0.00294	0.15158
0.5	0.34537	0.35624
1	0.28505	0.26745
1.5	0.22765	0.24326
2	0.1819	0.18223
2.5	0.14648	0.16124
3	0.11703	0.12069
3.5	0.096154	0.10712
4	0.079639	0.079403
4.5	0.065141	0.07143
5	0.054896	0.051992
5.5	0.04646	0.04783
6	0.039663	0.033859
6.5	0.03361	0.032188
7	0.02929	0.021889
7.5	0.02561	0.021803
8	0.022183	0.014002
8.5	0.019351	0.014895
9	0.017085	0.008818
9.5	0.015047	0.010289
10	0.013425	0.005419
10.5	0.011861	0.007211
11	0.010561	0.0032
11.5	0.009471	0.005145
12	0.008463	0.001757
12.5	0.007652	0.003754
13	0.006763	0.000826
13.5	0.006219	0.00281
14	0.005676	0.000231
14.5	0.005181	0.002165
15	0.004684	-0.00014
15.5	0.004347	0.00172
16	0.003896	-0.00037
16.5	0.003561	0.001409
17	0.003257	-0.00051
17.5	0.003058	0.001187
18	0.00276	-0.00059
18.5	0.002531	0.001027

Normalized and PMSB Simulation Data for Tank 2

time	Data	PMSB T1 -2.00E- 05
0	0.000526	0.000717
0.5	0.004146	0.005053
1	0.011579	0.013549
1.5	0.020301	0.02449
2	0.029236	0.036002
2.5	0.038126	0.046685
3	0.045914	0.055775
3.5	0.053519	0.062955
4	0.059933	0.068226
4.5	0.064383	0.071743
5	0.069028	0.073746
5.5	0.071736	0.074486
6	0.072591	0.074213
6.5	0.07207	0.073143
7	0.072712	0.071468
7.5	0.071414	0.069343
8	0.069749	0.066901
8.5	0.067572	0.064244
9	0.06539	0.061456
9.5	0.062051	0.058602
10	0.059966	0.055733
10.5	0.056015	0.052886
11	0.05327	0.050093
11.5	0.049979	0.047372
12	0.047031	0.044741
12.5	0.044213	0.042209
13	0.041554	0.039783
13.5	0.03914	0.037466
14	0.036776	0.03526
14.5	0.034191	0.033165
15	0.032345	0.031179
15.5	0.030115	0.0293
16	0.027862	0.027524
16.5	0.025965	0.025848
17	0.024198	0.024268
17.5	0.022718	0.02278
18	0.021132	0.021378
18.5	0.019982	

Normalized and PMSB Simulation Data for Tank 3

time	Data	PMSB T3
0	0.000418	3.96E-07
0.5	0.000691	7.73E-07
1	0.001199	1.88E-05
1.5	0.002089	0.00014
2	0.003337	0.000526
2.5	0.004992	0.001362
3	0.00698	0.002786
3.5	0.009183	0.00486
4	0.011824	0.007564
4.5	0.014358	0.010808
5	0.017328	0.014463
5.5	0.020588	0.018377
6	0.023589	0.022399
6.5	0.026484	0.026392
7	0.029439	0.030238
7.5	0.032487	0.033844
8	0.035361	0.037141
8.5	0.037977	0.040082
9	0.04073	0.042641
9.5	0.042617	0.044806
10	0.044239	0.04658
10.5	0.045933	0.047974
11	0.0481	0.049008
11.5	0.047473	0.049707
12	0.048287	0.050096
12.5	0.049338	0.050206
13	0.048519	0.050066
13.5	0.048265	0.049704
14	0.04812	0.049149
14.5	0.047896	0.048426
15	0.046831	0.047561
15.5	0.046234	0.046576
16	0.045351	0.045492
16.5	0.043721	0.044328
17	0.042965	0.043101
17.5	0.041113	0.041825
18	0.039368	0.040515
18.5	0.038941	0.039183

Normalized and PMSB Simulation Data for Tank 4

time	Data	PMSB T4
0	0.003631	8.41E-06
0.5	0.001649	8.07E-06
1	0.00162	7.87E-06
1.5	0.001708	9.52E-06
2	0.001916	2.05E-05
2.5	0.002278	5.86E-05
3	0.002695	1.54E-04
3.5	0.003283	0.000344
4	0.003992	0.000672
4.5	0.00485	0.001177
5	0.005432	0.001888
5.5	0.006699	0.002823
6	0.008324	0.003987
6.5	0.008728	0.005371
7	0.009818	0.006954
7.5	0.011516	0.00871
8	0.01321	0.010604
8.5	0.015289	0.012599
9	0.015362	0.014657
9.5	0.017529	0.016741
10	0.019555	0.018815
10.5	0.021719	0.02085
11	0.024233	0.022818
11.5	0.02442	0.024695
12	0.024683	0.026464
12.5	0.02639	0.028109
13	0.028889	0.02962
13.5	0.029845	0.030989
14	0.030928	0.032213
14.5	0.032513	0.033289
15	0.033382	0.034219
15.5	0.034252	0.035005
16	0.035344	0.035652
16.5	0.036018	0.036164
17	0.036727	0.036548
17.5	0.036775	0.036811
18	0.036378	0.036961
18.5	0.036433	0.037005