

**RADIOTRACER INVESTIGATION OF AN AEROBIC TANK OF A
WASTEWATER TREATMENT PLANT**

BY

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DECLARATION

This thesis is the result of research work undertaken by **LUABANYA MUBABINGE John Salem** towards award of the M.Phil. Nuclear Science and Technology in the Department of Medical Physics, School of Nuclear and Allied Sciences (SNAS), University of Ghana, under the supervision of **Professor C.P.K. Dagadu** and **Dr. Hannah A. Affum**.

This work has not been submitted previously, either in whole or in part, for a degree at this or any other University.

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DEDICATION

This work is dedicated to my wife **MUJINGA KATABALEY Esther**, my sons **LUABANYA WANZAMBI Salem** and **LUABANYA LUKANDA Vincent** and my mother **BANDEJA MUKENGE Anne**.

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LIST OF ABBREVIATIONS

WHO	World Health Organization
WWTPs	Waste Water Treatment Plants
IAEA	International Atomic Energy Agency
WWT	Waste Water Treatment
WW	Waste Water
RTD	Residence Time Distribution
MRT	Mean Residence Time
NAC	Nuclear Applications Centre
NNRI	National Nuclear Research Institute
DAS	Data Acquisition System
PMS	Perfect Mixers in Series
PMSE	Perfect Mixers in Series with Exchange

LIST OF SYMBOLS AND CONSTANTS

$E(t)$	Normalized RTD function
$C(t)$	Tracer concentration
t	Time
t_m	Exchange time constant
τ	Mean Residence Time
V	Tank volume
Q	Volumetric flow rate
σ^2	Variance
$C_{\text{exp}}(t)$	Experimental count rate
$C_{\text{bkg}}(t)$	Background count rate
$C(t_i)$	Count rate
$C_o(t)$	Dirac pulse
$n_c(t)$	Corrected count rate
$n_m(t)$	Measured count rate
λ	Decay constant

$t_{1/2}$	Half life
$F(t)$	Area of the curve
δ	Dirac impulse function
P_e	Peclet number
J	Number of mixing cells
α	Exchange flow rate ratio
K	Relative volume
M_0	Zeroth moment
M_1	First moment
f_d	Fraction of dead volume
V_{eff}	Effective volume of the tank
Q_1/Q	Volumetric flow rate ratio

ABSTRACT

Water is used in almost all human activities and large amounts of wastewater are produced every time. Wastewater need to be treated before it is discharged into the environment because it contains possible harmful substances which can pollute the environment and threaten life. Waste water treatment methods vary from industry to industry according to the process utilized. In most cases, the contaminants are not fully removed from waste water before discharge, due to certain malfunctions such as stagnant regions and short circuiting (bypassing or channeling) in the various processing tanks or units of treatment plants. Radiotracer residence time distribution methodology can be effectively used to pinpoint malfunctions or anomalies in process vessels and to consequently optimize performance. In this study, radiotracer residence time distribution methodology was used to determine the hydrodynamic parameters of the aerobic digester of an effluent treatment plant. 700 mCi of Technicium-99 m was introduced as a Dirac signal into the inlet of the digester of dimensions 11.50 m long, 2 m wide and 1.65 m deep. The volumetric flow rate into the digester was 1 m³/h. The concentration of radiotracer in the exit stream of the digester was determined using on-line tracer monitoring method. Sodium iodide NaI(Tl) scintillation detectors were installed at the inlet and exit streams of the digester to monitor tracer concentration directly. The experimental residence time distribution (RTD) data measured at the outlet of the digester was corrected for background, decay and normalized to obtain the required RTD function (E(t) curve). The method of moments was then used to determine the MRT and evaluate the RTD parameters. The experimental mean residence time (MRT) was far less than the theoretical MRT calculated with respect to the volume and flow rate. In this case, the percentage effective volume was estimated to 11.4 % translating into approximately 88.6

% dead volume in the digester. Using an RTD Software to model the flow structure in the digester, it was observed that the perfect mixers in series with exchange model best described the flow structure.

CHAPTER ONE

INTRODUCTION

In this chapter, the background of this study, problem statement and justification of the study are presented. The objectives and the scope of study are also stated.

1.1 BACKGROUND

World Health Organization (WHO) estimates that up to 80% of illnesses and infections in the world result from inadequate treatment of sewage and thus insufficient amount of clean water (Garbowski et al., 2018).

Water is used mainly in three different domains: Agriculture, Industry and Domestic. From these different uses of water, large amounts of wastewater are produced all the time (Bayoumi, 2007). Wastewater is a valuable resource of clean water, especially with recurring droughts and water shortages in many areas of the world. However, wastewater contains many harmful substances and cannot be released back into the environment or recycle until it is treated; hence the importance of wastewater treatment plants (WWTP) (Farooq et al., 2003).

WWTPs offer means through which pollutants in wastewater are reduced to a level which is safe for re-use. An efficient use and reuse of water is important in order to sustain our way of life (Chong et al., 2010). An ever increasing water use due to increasing population, calls for more research in the area of wastewater treatment which will lead to better knowledge and understanding of wastewater treatment processes in order to make wise decisions for water management and use (Elena et al., 2013).

WWTPs are complicated systems, where the processes of mixing, separation, aeration, biological and chemical reaction occur.

Optimized plant designs and operation of flow systems such as WWTPs are important and nuclear techniques offer the means for performance measurements. These techniques have been utilized on industrial scales to provide efficient solutions to operational problems resulting in savings in cost, materials and energy (Coarasa, 2004).

1.2 PROBLEM STATEMENT

The performance of WWTPs depends on the flow dynamics of the units (Cockx et al., 2001). The fluid dynamic properties of such systems are not yet well understood which makes the prediction of important process parameters difficult (IAEA, 2011). Lapses in design greatly affect the flow dynamics, hence, the performance of the plant. In most cases, due to the poor performance of WWTPs, contaminants in waste water are not fully removed before discharge into the environment resulting in environmental pollution. There is, therefore, the need to study the hydrodynamic parameters of the digester to ascertain its design parameters and efficiency

1.3 JUSTIFICATION OF STUDY

The study will lead to the identification of flow models that better describe the hydrodynamic parameters of WWTPs units, thus helping to achieve a reliable design.

Reliable design implies WWTPs will be optimized for operating conditions in order to eliminate or reduce environmental pollution.

1.4 OBJECTIVES

The main objective of the study is to determine hydrodynamics parameters of a digester of an effluent treatment plant using radiotracer residence time distribution (RTD) methodology.

The specific objectives are:

1. To determine the retention time curve of the digester;
2. To determine the mean residence time (MRT) of the digester
3. To determine the flow structure through RTD modeling.

1.5 SCOPE OF STUDY

The digester of the waste water treatment plant will be the unit of interest for the investigation. Technicium-99m (Tc-99m) will be used as the radiotracer for the study. The experiment will be carried out at the WWTP of a fruit juice manufacturing company in Accra. RTD software available at the Nuclear Applications Centre (NAC) of National Nuclear Research Institute (NNRI) will be used for data modeling.

1.6 ORGANIZATION OF THESIS

The thesis would be in the chronological order of five chapters. Chapter one is an introduction to the research that provides an overview of the current state of knowledge relevant to the study. Chapter two also reviews existing literature relevant to the research problem. Chapter three focuses on the experimental, methodology and calculations

framework for the study. The results obtained are presented and discussed in chapter four. Chapter five gives the conclusions of the study and appropriate recommendations.

CHAPTER TWO

LITERATURE REVIEW

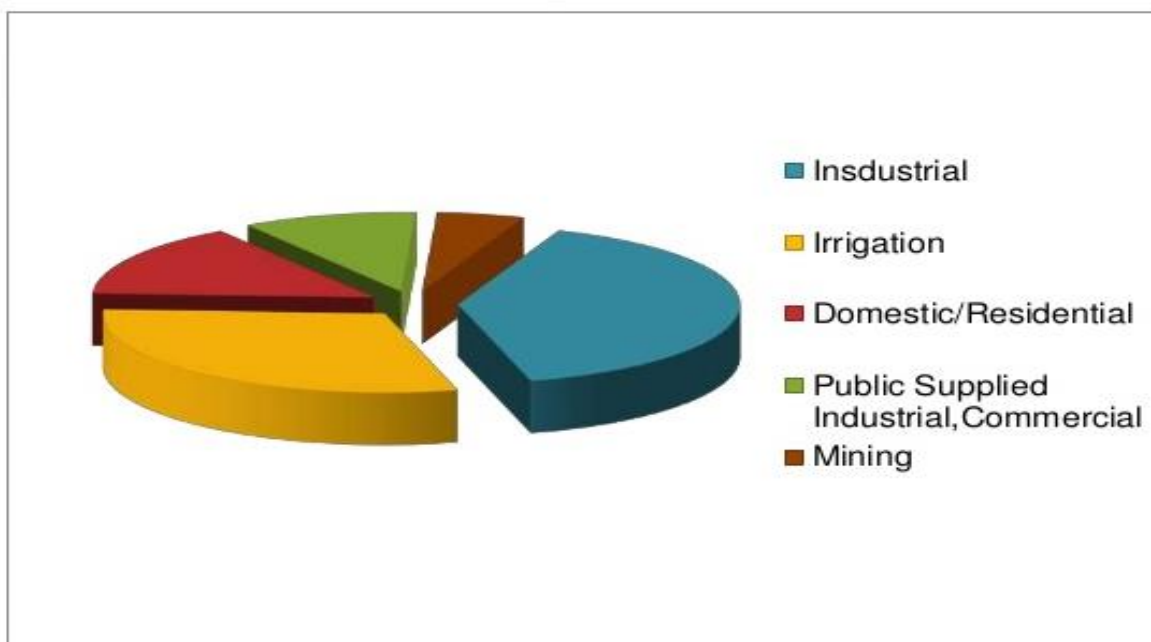
2.1 WASTEWATER

Water is necessary for human survival and basic to our lives. Population growth, coupled with an increase in human activities is unavoidably resulting in waste generation which threatens the availability of clean water. This is evident in global water pollution levels (Simi & Mitchell, 1999). Recurrent droughts and water shortages in many areas of the world further aggravate the situation (Graham, 2013).

Wastewater is defined as used water discharged from homes, businesses, industries, commercial activities and institutions; a mixture of water and dissolved or suspended substance (Waskom & Neibauer, 2012). It is categorized according to its sources of origin (A. Brief, 2012):

- Domestic wastewater is effluent consisting of black water like excreta, urine and fecal sludge and greywater.
- Industrial/commercial wastewater is used water from commercial establishments and institutions including hospitals, industrial effluent, storm water and urban run-off.

Figure 2.1 is a graph of the contribution of wastewater from the afore-mentioned sources.



**Figure 2.1 Wastewater distribution
The different sources of wastewater and the amount of the production**

2.2 WASTE WATER TREATMENT PLANT

Wastewater treatment is a process used to remove contaminants from wastewater or sewage and convert it into an effluent that can be returned to the water cycle with minimum impact on the environment, or directly reused. Wastewater contains contaminants in which bacteria, chemicals and other toxins are included. The objective of WWTP is to reduce or remove the contaminants in water before discharge back into the environment.

Chemical or physical wastewater treatment plants and biological wastewater treatment plants are the types of wastewater treatment plants. In the later, biological matter and bacteria are used to break down waste matter, while in the former, chemical reactions are

used to treat wastewater. Wastewater from households and business premises are treated by biological treatment processes. Physical wastewater treatment plants are mostly used to treat wastewater from industries, factories and manufacturing firms.

This is because most of the wastewater from these industries contains chemicals and other toxins that can largely harm the environment (USEPA, 1998).

In WWTPs, unit operations and processes are grouped together in a variety of configurations to produce different level of treatment, commonly known as physical, chemical and biological unit operations (Nations U., 2003).

2.2.1 Stages of wastewater treatment

There are various stages in the treatment of waste water. These include the preliminary, primary, secondary and tertiary treatment stages (USEPA, 1998). These stages are characterised by the equipment employed and nature of the treatment.

1. Preliminary treatment

The first treatment stage in WWT consists of the removal of large debris, heavy inorganic and coarse biodegradables. (Buchanan, 2015). Preliminary treatment includes screening and comminution and grit removal (Elena et al., 2013). Typical equalization tanks are installed to determine the uniformity between physical and chemical properties of the influent (Iaea-tecdoc-, 2003).

2. Primary treatment

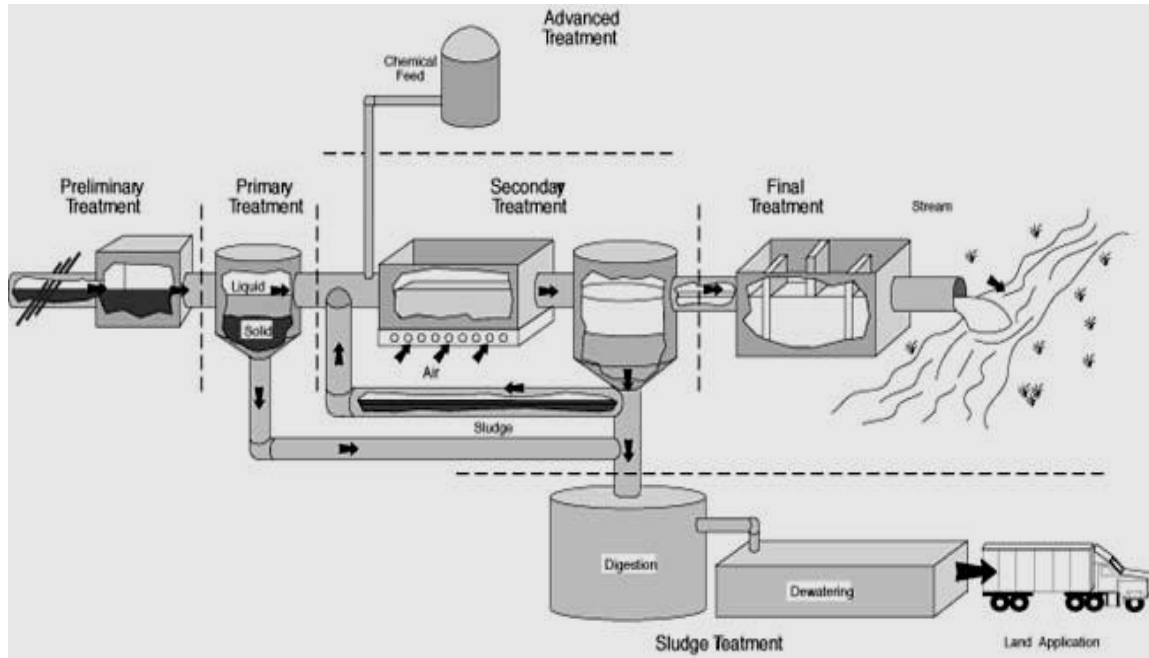
The objective of primary treatment is the removal of settleable organic and inorganic solids by sedimentation as well as materials that will float (scum) by skimming. Primary sedimentation tanks can be round or rectangular basins, the depth can vary between 3 to 5 m, with hydraulic retention time between 2 and 3 hours (Rmsawwa, 2004).

3. Secondary treatment

Secondary treatment includes two units: aeration tank and secondary clarifier (For et al., 2006). In the aeration tank, commonly called biological aerobic tank, air is used as a mixer and to promote the expansion of micro-organisms which create a sludge (Giho, 2004). Sludge produced in excess of process requirements is wasted or discharged from the treatment and removed from the secondary clarifier (Rmsawwa, 2004).

4. Tertiary treatment

At this stage disinfectants are added to the water. The main aim of disinfection at wastewater treatment facilities is to remove or kill the micro-organisms in the water (IAEA, 2011). Before the water is discharged into the environment or reuse, the effluent from the sedimentation tank is usually disinfected with chlorine.



**Figure 2.2 Flow circuit of a wastewater treatment plant
The different process and treatment of wastewater in the industrial plant before
discharge**

2.2.2 DIGESTOR

Digestion, considered the most important part of the wastewater treatment process, involves the break down of organic matter in the presence or absence of oxygen (Å & Leclerc, 2005). The digestion process occurs in the digester.

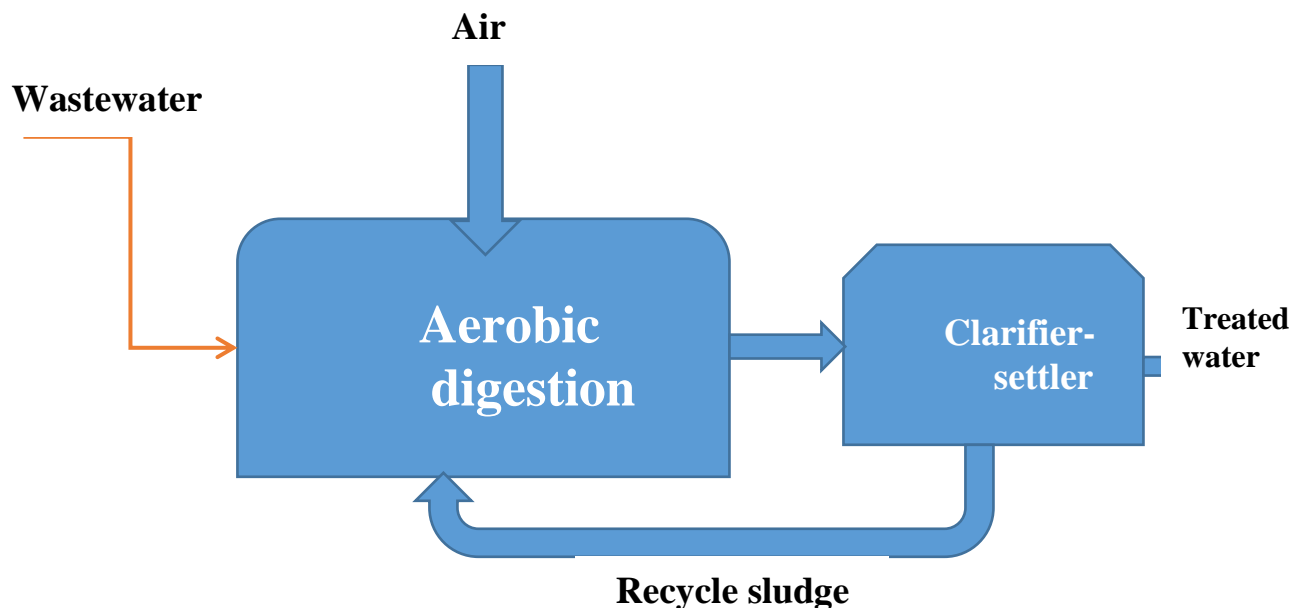


Figure 2.3 Principle of aerobic digestion

Anaerobic digestion is an energy-efficient process in which microorganisms transform organic matter in the wastewater into biogas in the absence of oxygen. To achieve this oxygen-free environment, entry of air into anaerobic tanks is prevented, typically by a gastight cover. The process offers several benefits over aerobic treatment, including lower energy requirements, less chemicals, and less sludge production. The sludge is stable and safe to use as a soil enhancer. Methane-rich biogas is also produced through the anaerobic process, which can be treated and used as a renewable energy source, helping save money and the environment.

With aerobic treatment, microorganisms convert organics into carbon dioxide and new biomass in the presence of oxygen. Aerobic microorganisms require oxygen so air must be continuously circulated through the tanks. Forced air from an air blower or compressor

is mixed with the wastewater, where the aerobic bacteria feed on the waste in the water. (Nelson & Holder, 2009).

Although aerobic systems require higher amounts of energy for aeration and produce more sludge than anaerobic systems, they play a necessary role in the wastewater treatment train. These systems allow industrial processes to meet even the strictest environmental requirements so that wastewater can be discharged safely. (Lee et al., 2006).

2.3 RADIOTRACERS, PRODUCTION AND DETECTION

Radiotracer is a substance or matter that has the same property as the material which it traces (IAEA, 2008). They are used for the identification, observation and following the behaviour of various physical or biological processes (dispersion, mixing, kinetics and dynamics), which occur either instantaneously or in a given lapse of time. There are many kinds of tracers (IAEA, 2008). Intrinsic tracers or internal tracers are chemical tracers containing an isotope of one of the molecules of natural elements (IAEA, 2011). For example, in the case of water, Tritium ($^1\text{H} \text{}^3\text{H}^{16}\text{O}$) measured by nuclear techniques (in practice liquid scintillation counting) is an intrinsic tracer. In this case, the water molecule is traced from the inside, in the intimacy of its nucleus, consequently the water tracer will (in practice) follow all movements and reactions of water itself.

Extrinsic tracer or external tracer is a physical radioactive tracer which is obtained from the atoms that have the same characteristics (Roberge et al., 1991). Belonging to this category are all the substances that allow tracing outside the molecular or ionic structure.

For example, Na¹³¹I and ⁵¹Cr-EDTA are examples of extrinsic tracers for water (IAEA, 2011). Table 2.1 shows commonly used radiotracers in industry

Table 2.1 Commonly used radiotracers in industry (IAEA, 2011)

Isotope	Half-life	Radiation and Energy (MeV)	Chemical Form	Tracing of phase
Tritium (3H)	12.6 y	Beta, 0.018(100%)	Tritiated water	Aqueous
Sodium-24	15 h	Gamma: 1.37(100%) 2.75(100%)	Sodium carbonate	Aqueous
Bromine-82	36 h	Gamma: 0.55 (70%) 1.32 (27%)	Ammonium bromide, p-dibrom-benzene, Dibrobiphenyl CH ₃ Br, C ₂ H ₅ Br	Aqueous Organic Organic Gases
Lanthanum-140	40 h	Gamma: 1.16 (95%) 0.92 (10%) 0.82(27%) 2.54 (4%)	Lanthanum chloride, Lanthanum oxide	Aqueous/Solids Solids
Gold-198	2.7 d	Gamma: 0.41 (99%)	Chloroauric acid	Aqueous/Solids
Mercury-197	2.7 d	Gamma: 0.077(19%)	Mercury metal	Mercury
Iodine-131	8.04 d	Gamma: 0.36 (80%) 0.64 (9%)	Potassium or Sodium iodide, Iodobenzene	Aqueous Organic
Chromium-51	28 d	Gamma: 0.320 (9.8%)	Cr-EDTA, CrCl ₃	Aqueous
Technetium-99m	6 h	Gamma: 0.14 (90%)	Sodium pertechnetate (TcO ₄ -)	Aqueous
Scandium-46	84 d	Gamma: 0.89(100%) 1.84(100%)	Scandium oxide Scandium chloride ScCl ₃ (Sc ₃₊)	Solids Aqueous/Solids
Xenon-133	5.27 d	Gamma: 0.08 (100%)	Xenon	Gases
Krypton-85	10.6 y	Gamma: 0.51(0.7%)	Krypton	Gases
Krypton-79	35 h	Gamma: 0.51 (15%)	Krypton	Gases
Argon-41	110 min	Gamma: 1.29(99%)	Argon	Gases

2.3.1 Advantages of radiotracers

Radiotracers possess a number of advantages including the following according to (IAEA, 2011)

1. They have high detection sensitivity for extremely small concentrations, for instance, some radionuclides may be detected in quantities as small as 10^{-17} grams.
2. The amount of radiotracer used is virtually insignificant. For example, 1 Ci of ^{131}I - weighs 8 μg , while 1 Ci of ^{82}Br - weighs only 0.9 μg . That's why, when injected, they do not disturb the dynamics of the system under investigation.
3. They offer possibility of "in-situ" measurements, providing information in the shortest possible time.
4. A gamma emitting radiotracer can be measured through radiation transmission, from the outside of a pipe or vessel. This is of special importance for many industrial plant studies.
5. Disappearance of the radiotracer from the medium under investigation through radioactive decay allows repetition of experiments on the same location with the same tracer.
6. Radioactive tracer can be selective. Several tracers may be employed simultaneously and their characteristic radiation emissions be measured.

2.3.2 Radioisotope generators

Radiotracers are produced by direct neutron activation in a nuclear reactor and by radionuclide generators (Velikyan, 2015). A generator is a self-contained system housing a parent/daughter mixture in equilibrium. It is designed to produce the daughter for tracing purposes (IAEA, 2011).

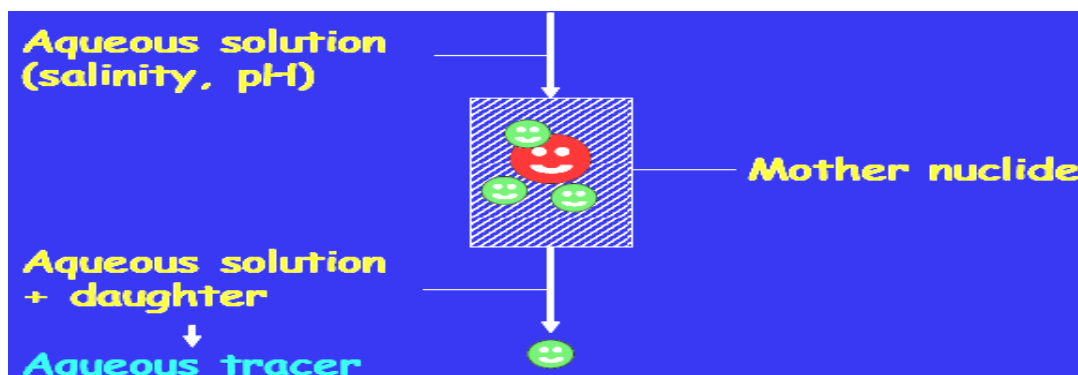


Figure 2.4 Principle of radioisotope generator

In the nuclear genetic relationship, one radionuclide (the mother) produces another radionuclide (the daughter) by radioactive decay. In a radionuclide generator the nuclear properties are such that the mother nuclide has a longer half-life (less unstable) than the daughter nuclide (more unstable) (Fure et al., 2008).

Technetium-99m is a metastable nuclear isomer of technetium-99 produced in $^{99}\text{Mo}/^{99\text{m}}\text{Tc}$ generator. As indicated by the “m” after its mass number 99, it is a decay product whose nucleus remains in an excited state that lasts much longer than is typical.

Tc-99m decays mainly by gamma emission, slightly less than 88% of the time ($^{99\text{m}}\text{Tc}/^{99}\text{Tc}+\gamma$). About 98,6% of these gamma decays result in 140,5 keV gamma rays and the remaining 1,4% are to gammas of a slightly higher energy at 142,6 keV. These are the radiations that are picked up by a detector when $^{99\text{m}}\text{Tc}$ is used as a radioactive tracer (Borroto et al., 2003).

2.3.3 Choice of radiotracers

The important factors to consider in selecting radiotracers include the following (Coarasa, 2004):

- The tracer must have the same physical/chemical propriety as the material or system to be studied
- The tracer must have sufficient half-life and specific activity with respect to the process being investigated
- The tracer must possess sufficient energy for detection.

2.3.4 Detection of radiotracers

The operation of any radiation detector depends basically on the manner in which the radiation to be detected interacts with the material of the detector itself. The fundamental mechanism is that radiation interacts and loses their energy to the material of the detector, thus giving rise to the detector response. The interaction time is very small (typically a few nanoseconds or 10^{-9} in gases or a few picoseconds or 10^{-12} in solids) (IAEA 2008). Radiation detectors are categorized into two (2) - ionization detectors and scintillation detectors. Scintillation detectors are used in radiotracer investigations because of their high efficiency and precision (IAEA, 2008). Sodium Iodide, NaI(Tl), detector is one of the scintillation detectors, which is composed of Sodium Iodide doped with Thallium (Lewellen, 2008).

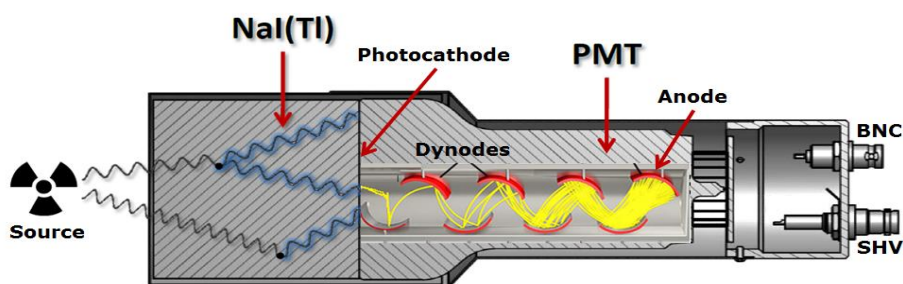


Figure 2.5 Structure of the scintillation detector

2.4 RESIDENCE TIME DISTRIBUTION

2.4.1 Definition

The residence time distribution (RTD) is a probability distribution function that describes the amount of time that a radiotracer spends in a reactor (Curie, 2008).

The distribution function is represented by an external residence time distribution, $E(t)$ (Farooq et al., 2003) given by equation 2.1:

$$E(t) = \frac{c(t)}{\int_0^{\infty} c(t)dt} \quad 2.1$$

Where:

$C(t)$ is the concentration of tracer measured at the outlet of the unit at time 't'.

The MRT is given by the first moment of the residence time distribution (Bayoumi, 2007) as indicated by equation 2.2:

$$t_m = \frac{\int_0^{\infty} tE(t)dt}{\int_0^{\infty} E(t)dt} = \int_0^{\infty} tE(t) dt \quad 2.2$$

Where:

t_m is MRT,

t is the time the fluid spends in the unit and

$E(t)$ is normalized RTD fuction.

The theoretical MRT (τ) is calculated from the volume, V , of the unit with constant flow rate Q using equation 2.3:

$$\tau = \frac{V}{Q} \quad 2.3$$

The theoretical MRT τ is equal to experimental MRT t_m when there are no dead or stagnant zones within the reactor. MRT is the first moment which gives significant information about the behavior of the function $E(t)$.

The variance(σ^2) is the second moment which determines the degree of dispersion around the mean and is given by equation 2.4.

$$\sigma^2 = \int_0^{\infty} (t - t_m)^2 E(t) dt \quad 2.4$$

2.4.2 DETERMINING THE RTD

The RTD is obtained by an impulse-response method; injection of a tracer at the inlet of a system and recording the concentration-time curve $C(t)$ at the outlet as seen in Figure 2.6 (IAEA, 2011). A radiotracer is injected in the system under investigation and a detector is placed at inlet of the system to confirm the presence of tracer in the system. The second detector located at the outlet of the system determines the time that tracer exists the system.

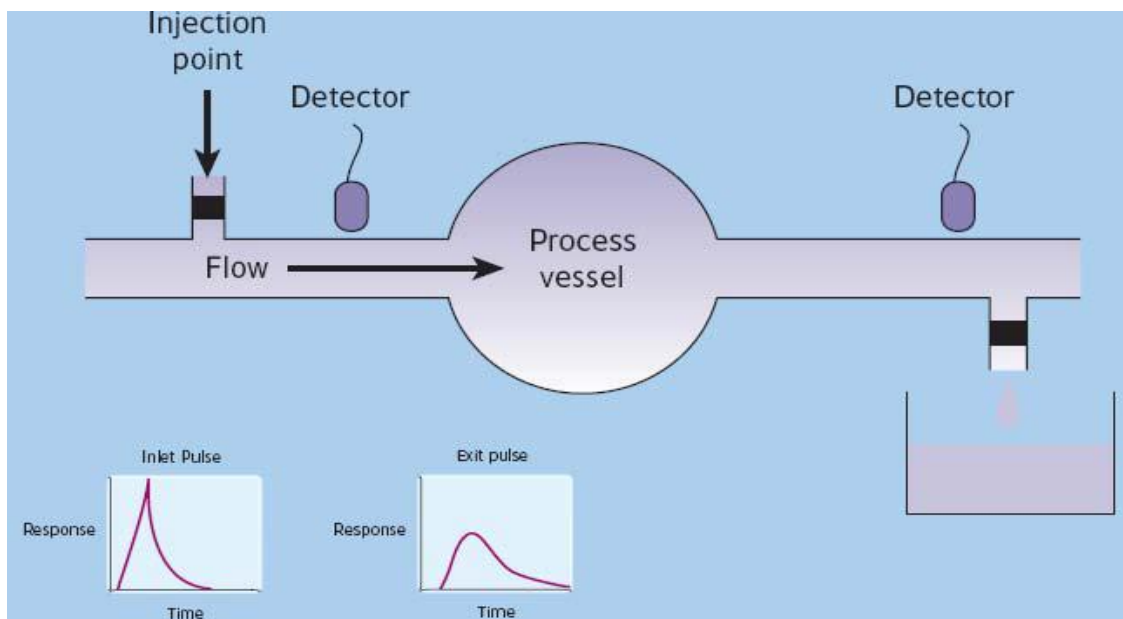


Figure 2.6 Principle of RTD method

2.5 EXPERIMENTAL RTD

2.5.1 Radiotracer injection

The mode of radiotracer injection is very important in determining the residence time and mixing characteristics of a vessel (Baléo et al., 2001). The injection can be either Dirac or pulse and step.

The pulse injection or Dirac pulse is the instantaneous introduction of tracer in the system (Nameche & Vasel, 1998) as shown in Figure 2.7

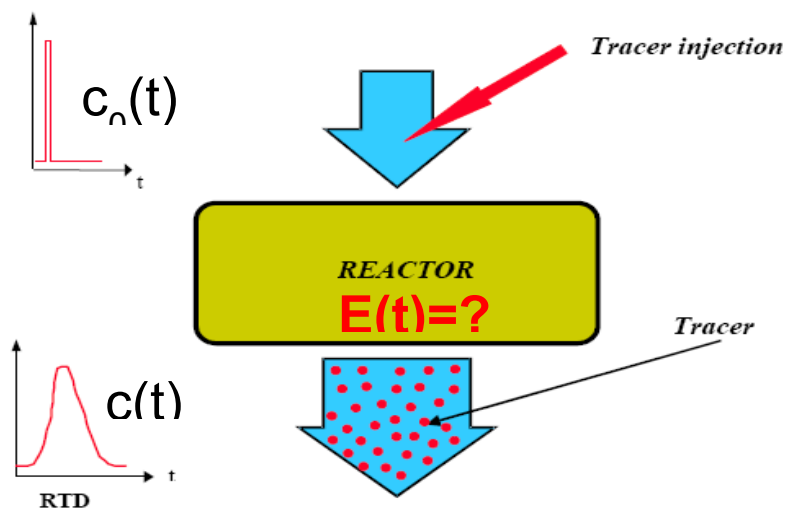


Figure 2.7 Principle of radiotracer injection

$$C(t) = C_0(t) * E(t)$$

2.5

$$C(t) \equiv E(t)$$

Where $C(t)$ is the concentration of tracer measured at outlet at time t . ($C(t)$ approximately equals the residence time distribution given by $E(t)$) and $C_0(t)$ is the Dirac pulse (IAEA, 2007).

2.5.2 Radiotracer monitoring

The concentration of a radiotracer injected in the system can be measured using the on-line or sampling (offline) method (Simi & Mitchell, 1999).

In employing the online technique, the detectors are installed at selected locations on the system to monitor tracer concentration directly, This method is preferred to the off-line approach where samples of the investigated media are collected and later counted using a suitable radiation detector.

2.5.3 Data acquisition system

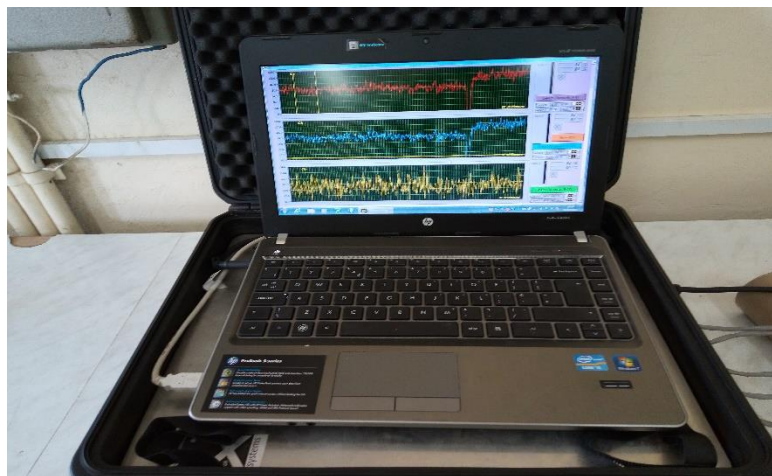


Figure 2.8 Data acquisition system for online radiotracer tests

A data acquisition system (DAS), as shown in Figure 2.8, is the basic equipment for online radiotracer RTD measurements. The DAS ensures collection, treatment and visualization of the data (IAEA, 2011).

2.5.4 Treatment of experimental RTD

Normally, the data from experimental RTD contain statistical fluctuations and other parasitic influences (IAEA, 2008). The experimental RTD data goes through the following treatment:

1. Background correction

Background radiation has influence on the data and must be eliminated. Before injection of radiotracer into a unit, measurement of the background radiation level is necessary (Cockx et al., 2001). The correction of the experimental RTD data for background radiation is carried out by the relation below:

$$C(t_i) = C_{exp}(t_i) - C_{bkg} \quad 2.6$$

Where:

$C(t_i)$ is the Count rate

$C_{exp}(t_i)$ is the Experimental count rate

C_{bkg} is the Background count rate

2. Radioactive decay correction

Since radioisotope tracers decay exponentially with time, it is necessary to apply decay correction to the measured data (otherwise, more weight would unduly be given to early measurements) (IAEA, 2008).. The decay corrected count rate $n_c(t)$ is given as:

$$n_c(t) = n_m(t) \exp(\lambda t) = n_m(t) \exp\left(\frac{0.693t}{t_{1/2}}\right) \quad 2.7$$

Where:

λ is the decay constant,

t is the time

$t_{1/2}$ is the half-life

3. Filtering (or Smoothing)

Filtering is applied to eliminate, or at least lessen, vacillation due to counting statistics or electronic noise (Ramamoorthy N., 2004). Various methods for filtering a signal are available. The effective method used for filtering the shape of the experimental RTD is Fourier transform because it can filter many high frequencies.

4. Data extrapolation

Data extrapolation is needed when the end of the measured tracer curve is missed for different reasons. The objective of this method is to extend the tracer curve in some way. The exponential decay function is used to adjust the experimental curve, such that the data decrease exponentially at the end (Trkov, 2009).

5. Normalization

Area normalization is the last corrective measure performed on the experimental RTD data. Firstly, the factors that affect the area of the curves are eliminated. Secondly, is used to calculate the moments. Thirdly, the curve obtained from area normalization represents RTD of the system (IAEA, 2008).

When, RTD modelling of data is requested the area normalization is obligatory. The tracer concentration curve is normalized by dividing each data point by the area under the curve (i.e. the total count number) using the following equation:

$$E(t) = \frac{n_c(t)}{\int_0^{\infty} n_c(t) dt} \quad 2.8$$

Where:

$n_c(t)$: is the corrected count rate

$E(t)$: is the normalized function

2.6 RTD MODELING

The treated RTD curve is then fitted to known theoretical RTD functions in the process of modelling using appropriate Software (Menon et al., 2019)

2.6.1 Ideal flow models

The ideal models represent two (2) circumstances (Rmsawwa, 2004). Plug flow and perfectly mixed flow.

In plug flow, the flow of fluid is convective and its RTD is represented by equation 2.9:

$$E(t) = \delta(t - \tau) \quad 2.9$$

Where

δ is the Dirac impulse function

t is the time

τ is the mean residence time

For perfectly mixed flows, the tracer is mixed perfectly in system. The flow is therefore represented by the expression:

$$E(t) = \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) \quad 2.10$$

The first moment (MRT) is $t=\tau$ and the second moment $\sigma^2=\tau^2$

2.6.2 Non ideal flows models

In practice, the flow systems are characterized by non-ideal; between plug flow and perfect mixer (Singh et al., 2008). The axial dispersion model and perfect mixing cells model are used to describe such flow systems (I.A.E.A, 2011).

In the axial dispersion model, the fluid is a superimposition of convection and some amount of dispersion. The expression of the RTD function is given by equation:

$$E(t) = \frac{1}{2} \left(\frac{P_e}{\pi \tau t} \right)^{1/2} \exp\left(-\frac{P_e(\tau-t)^2}{4\tau t}\right) \quad 2.11$$

Where

$E(t)$ is the RTD function

P_e is the Non-dimensional Peclet number

t is the time

τ is the mean residence time

Two parameters characterize this model: τ and P_e . MRT is time constant τ , and the variance is given by:

$$\sigma^2=2\tau^2/Pe. \quad 2.12$$

In the perfect mixing cells model, the flow is composed of perfect mixing cells in series.

The expression of RTD function is:

$$E(t) = \left(\frac{J}{\tau}\right)^J \frac{t^{J-1} \exp\left(-\frac{Jt}{\tau}\right)}{(J-1)!} \quad 2.13$$

Where J represent the number of cells.

The perfect mixers in series model is an alternative to the axial dispersed model where J replaces Pe and where the flow is dependent on the value of J. So $P_e \approx 2(J - 1)$.

The MRT= τ and the variance $\sigma^2 = \frac{\tau^2}{J}$.

Other non-ideal flow models consisting of slight extensions and modifications of the basic two mentioned above exist in an RTD software.

2.6.3 RTD modeling software

➤ Perfect mixers in series with exchange

In this model, the flow in the system passes through two volumes: active and stagnant volumes that exchange their flow, as shown in Figure 2.9. Four independent parameters characterize this model

$$\tau = \frac{JV_1}{Q}; \quad t_m = \frac{V_2}{\alpha Q}; \quad k = \frac{V_2}{V_1}; \text{ and } J \quad 2.14$$

τ is the MRT,

t_m is the exchange time between active volume and dead volume,

k is the relative volume,

V_1 is an active volume,

V_2 is the dead volume,

J is the number mixing of cells.

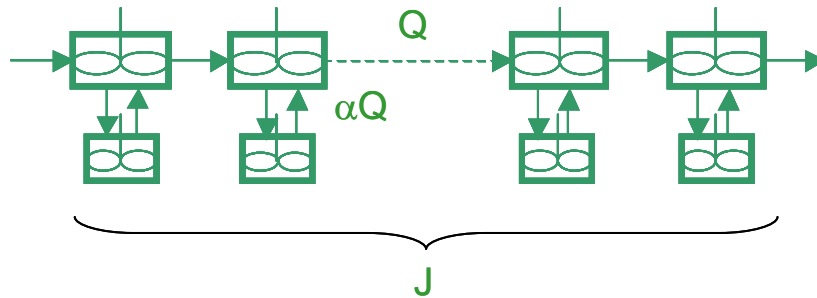


Figure 2.9 Perfect mixers in series with exchange model

➤ **Perfect mixers in parallel**

This model is the combination of two series model in parallel, as shown in Figure 2.10. In

this model, there are two times constants τ and τ_1 :

$$\tau = \frac{V}{Q_1}; \quad \tau_1 = \frac{V_2}{Q_2} \quad 2.15$$

Where:

V is the volume of the first series of J mixers, with flow rate Q_1 ,

V_2 is the volume of the second series of J_2 mixers,

Q_2 is the flow rate.

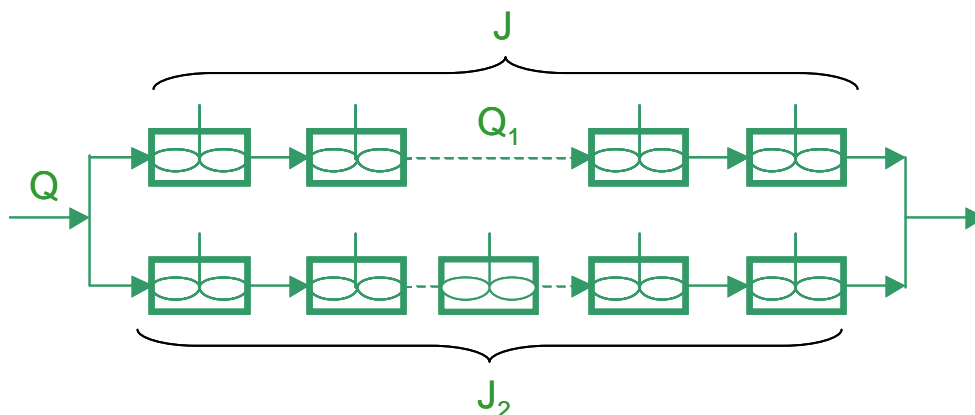


Figure 2.10 Perfect mixers in parallel

➤ **Perfect mixers with recycle**

In this model, the flow process is characterized by recycle flow, with flow rate Q_r .

The constant times are given by equation 2.16.

$$\tau = \frac{V}{Q+Q_r}; \quad \tau_2 = \frac{V_2}{Q_r} \quad 2.16$$

Where

τ is the constant time

V is the active volume

V_2 is the recycle volume

Q flow rate

Q_r recycle flow rate

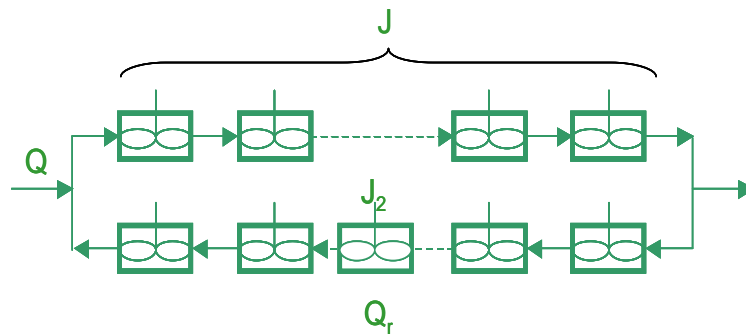


Figure 2.11 Perfect mixers with recycle

2.7 RADIOTRACER INVESTIGATION REVIEW

Wastewater flow investigations involving the use of radiotracers abound. Rivera et al (2014) employed radiotracer sodium pertechnetate ($\text{Na}^{99\text{m}}\text{TcO}_4^-$) to study the flow in two aerated tanks of Howard wastewater treatment plant in Panama city, Panama. The result

obtained showed that the mean residence time (MRT) was greater than the nominal value and there were no dead zones.

M. Sarkar et al (2017) carried out a radiotracer investigation of a pulp and paper mill effluent treatment plant to study the flow behavior and to locate system anomalies. This study, which used I-131 as tracer discovered that there were no dead zones and that the plant was working efficiently. Awet et al (2018) also investigated the hydraulic performance of an anaerobic pond in Kenya using radiotracer technique. A high percentage of dead volume was found to be present in the pond. Appiah et al (2019) analyzed the Residence Time Distribution of a waste water treatment unit of the Tema oil refinery using radioactive tracer technique by injecting Ga-68 into the unit of interest. The majority of work, show that, the hydrodynamics parameters of a chemical reactor can be determined using the tracer RTD methodology.

CHAPTER THREE

MATERIALS AND METHOD

In this chapter, the experiment conducted to achieve the study objectives is discussed. It provides a physical description of the aerobic digester and highlights the various steps of RTD formulation namely radiotracer selection, injection and data collection.

3.1 PLANT DESCRIPTION

This study was carried out on the aerobic digester of the effluent treatment plant at a fruit processing company that produces fresh cut fruit salads juices for export and for the Ghanaian market. These processes require the use of large quantities of water. Therefore, the efficient operation of the treatment plant is key in order to cut down on waste.

The digester consists of a rectangular steel tank of length 11.50 m, width 2 m and height 1.65 m as shown in Figure 3.1. It is equipped with three perforated pipe diffusers located at the footer of tank (Figure 3.2). The diffusers inject air, from a compressed air source, into the digester for agitation in order to constantly keep the solid waste suspended for effective degradation during the aerobic digestion process. Waste water from the primary sedimentation tank enters the digester at a volumetric flow rate of 1 m³/h.



Figure 3.1 Picture of rectangular Digester

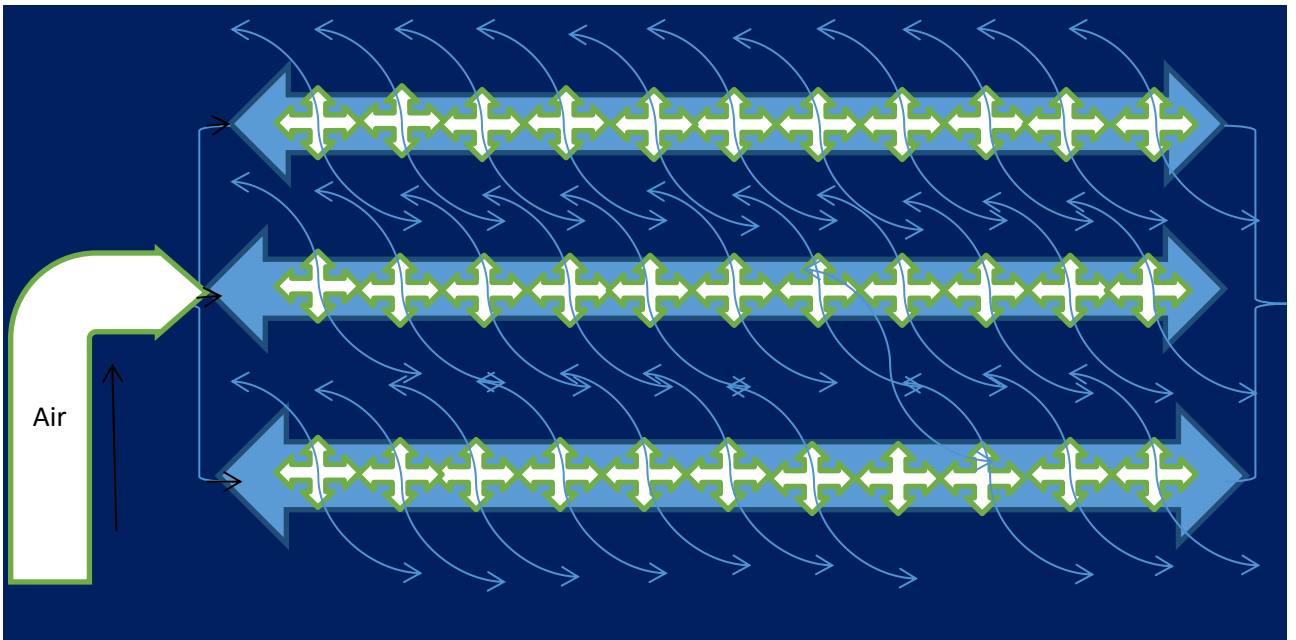


Figure 3.2 Schematic diagram of diffusers located inside the digester

3.2 EXPERIMENTAL

The experiment was carried with assistance from personnel of the Radiotracer unit of the National Nuclear Research Institute who helped during data collection. In order to adhere to safety procedures of using radioactive materials, the procedure of radioisotope tracer investigations as established by the International Atomic Energy Agency (IAEA, 2009) were followed during the investigation.

3.2.1. Radiotracer Selection and Injection

One of the most important aspects of a radiotracer test is the selection of a suitable radiotracer. In this study, based on the criteria of tracer selection as described in section 2.3.3 of chapter two and considering the availability of radiotracers, Tc-99m in the form of sodium pertechnetate was selected for the test.

The tracer, commonly used for cancer treatment, was collected from the Korle-Bu Radiotherapy Centre in Accra. The tracer was transported in a lead shield to the experimental site where about 700 mCi activity was loaded into a syringe and instantaneously injected into feed pipe of the digester. These activities are shown in Figure 3.3.



Figure 3.3 Tracer in a lead shield, Tracer loading and Tracer injection syringe

3.3 DATA ACQUISITION

The concentration of a radiotracer in the exit stream of a system can be determined by two methods, the sampling method and on-line method. In the current study, the on-line method was used to monitor the radiotracer. This was achieved by installing NaI(Tl) scintillation detectors in the inlet and exit streams of the digester. Signals from the inlet detectors provide indication of the tracer entering the system while the outlet detector signals the exit of the tracer from the system. The detectors were driven by ALTAIX Caesar 12 data acquisition system comprising a laptop computer and software for data collection. The attraction of this data acquisition system is that it ensures visualization of the data points during data collection as the experiment progresses.

It is worth mentioning that prior to tracer injection the data acquisition system was operated for about 20 minutes to record background radiation levels at the detection points.

A picture summary of data acquisition is shown in Figures.3.5,3.6 and 3.7. While the tracer concentration curve recorded at the exit of the digester at the end of the

investigation is presented in Figure 3.4. The raw data was taken through some treatment procedures and then analysed in the next chapter.

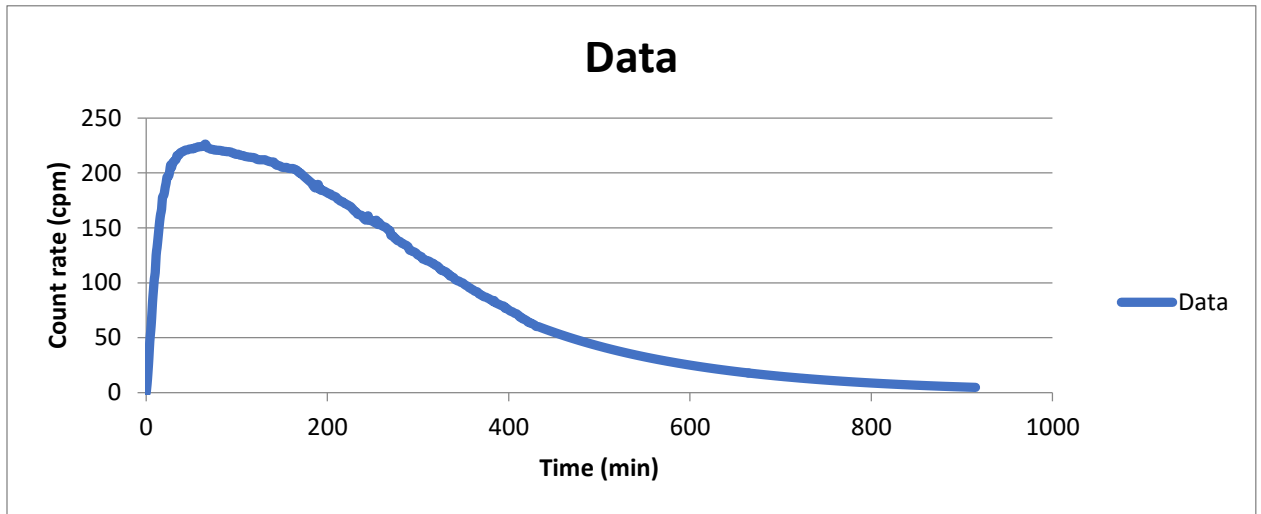


Figure 3.4 Tracer concentration data



Figure 3.6 Inlet detector



Figure 3.5 Outlet detector

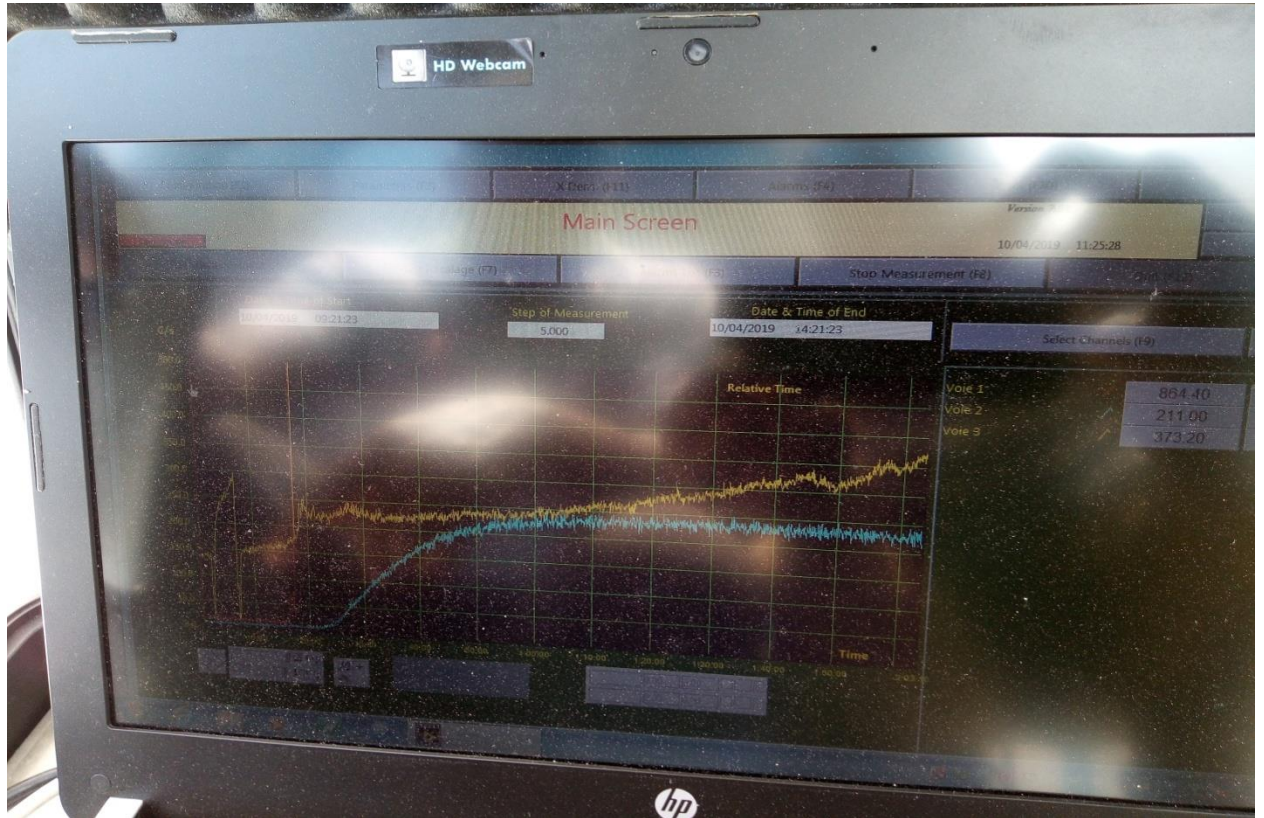


Figure 3.7 Data acquisition system

CHAPTER FOUR

RESULTS AND DISCUSSION

In this chapter, the results of the experimental investigations are discussed. The main tasks performed include data treatment, estimation of RTD parameters and mathematical modeling.

4.1 DATA TREATMENT

It is always necessary to remove possible parasite influences from the raw data before analyzing the results. In this study, the raw experimental data was corrected for background radiation and then normalized using RTD analysis software DTSPRO V4. (PROGEPI, 2000).

The need to correct for background radiation comes from the fact that, most industries use nucleonic gauges for process control. These gauges emit gamma radiation which together with other possible sources constitute background radiation. In order to account for background gamma radiation, radiation levels around the experimental setup were measured prior to the start of tracer injection. The experimental count rates were then determined from Equation 2.1. (Chapter 2).

The data, free of background radiation, was then normalized to convert the count rates into RTD functions as explained in section 2.5.4, Chapter 2. Plot of the normalized data (RTD) measured at the exit of the digester is shown in Figure 4.1

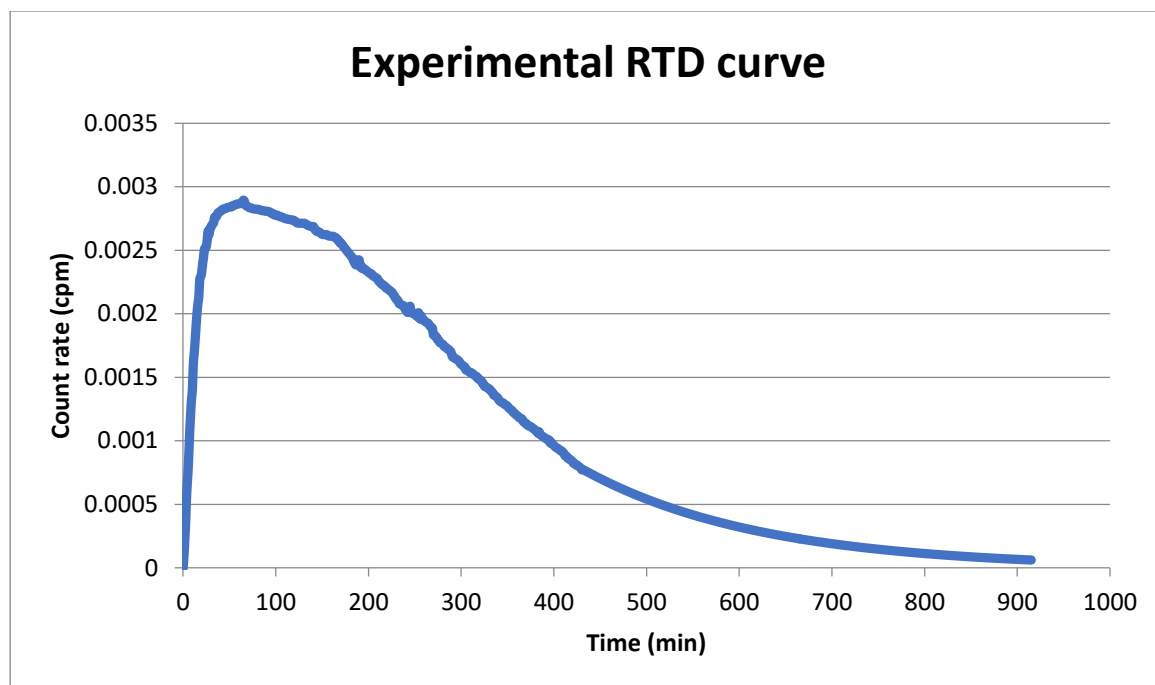


Figure 4.1 Normalized data (RTD) measured

4.2 CALCULATION OF HYDRODYNAMIC PARAMETERS

The mean residence time (MRT) is the most important hydrodynamic parameter of process vessels (Ham and Platzer, 2004). Experimentally it represents the average time taken by the tracer to travel between the injection and detection points and calculated using the method of moments (section 2.4.1; Chapter 2). Theoretically, the MRT reflects mass transfer phenomenon in the reactor and defines the relationship between the vessel volume and volumetric feed rate at a constant fluid density (Equation 4.1)

$$\tau = V/Q \quad 4.1$$

Where V is the volume of material in the vessel, Q is the volumetric flow rate and τ is the theoretical MRT of the fluid.

The values of the experimental and theoretical MRTs, as calculated, were used to determine the performance of the digester by evaluating the fraction of dead space (f_d) and hence the effective working volume using Equation 4.2.

$$f_d = 1 - \frac{\bar{t}}{\tau} = 1 - \frac{V_{eff}}{V} \quad 4.2$$

Where V_{eff} and V are effective and material volumes of the reactor.

The evaluated hydrodynamic parameters are reported in Table 4.1

Table 4.1 Evaluated hydrodynamic parameters

Volume of digester $V(m^3)$	Flow rate $Q(m^3/h)$	Theoretical MRT (h)	Experimental MRT (h)	Effective volume (m^3)	% effective volume
35	1	35	4	4	11.4

4.3 MODELING OF THE EXPERIMENTAL RTD

Modelling of experimental RTD is the last step in a tracer test and forms an essential aspect of data interpretation. Modeling helps to compare the behaviour of practical reactors to ideal conditions, describe the pattern of flow in a reactor and quantify the degree of mixing. In this study, the RTD analysis software was used to model the experimental data.

Complete mixing is assumed during the design of all mixing reactors. Therefore, the perfect mixers-in-series (PMS) model (Pant and Yelgoankar, 2002) was initially selected

to model the experimental data. However, after several attempts of curve fitting, the PMS model failed to fit properly with the experimental data.

Taking into consideration the process of mixing by air agitation in the digester, other combinations of the elementary flow models, including perfect mixers-in-parallel and perfect mixers-in-series with exchange (PMSE) models, were used to account for possible parallel flows.

Among these combinations, the PMSE model gave the best fit as shown in Figures. 4.2, 4.3 and 4.4. The model parameters of the PMSE (model with the best fit) are presented in Table 4.2.

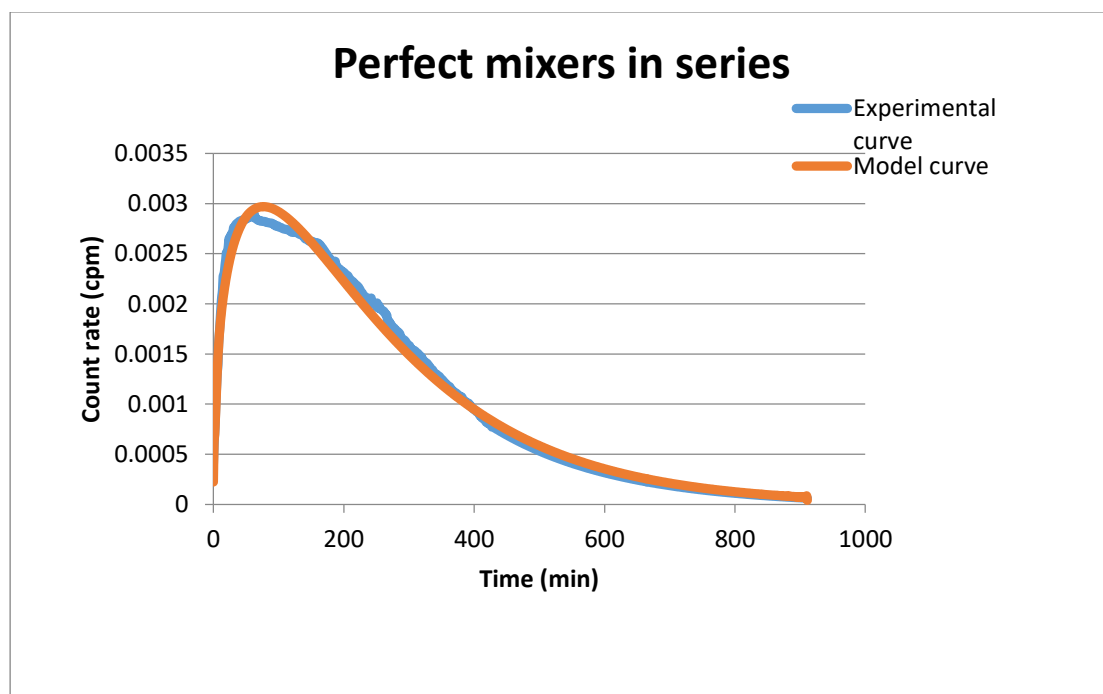


Figure 4.2 Perfect mixers in series model

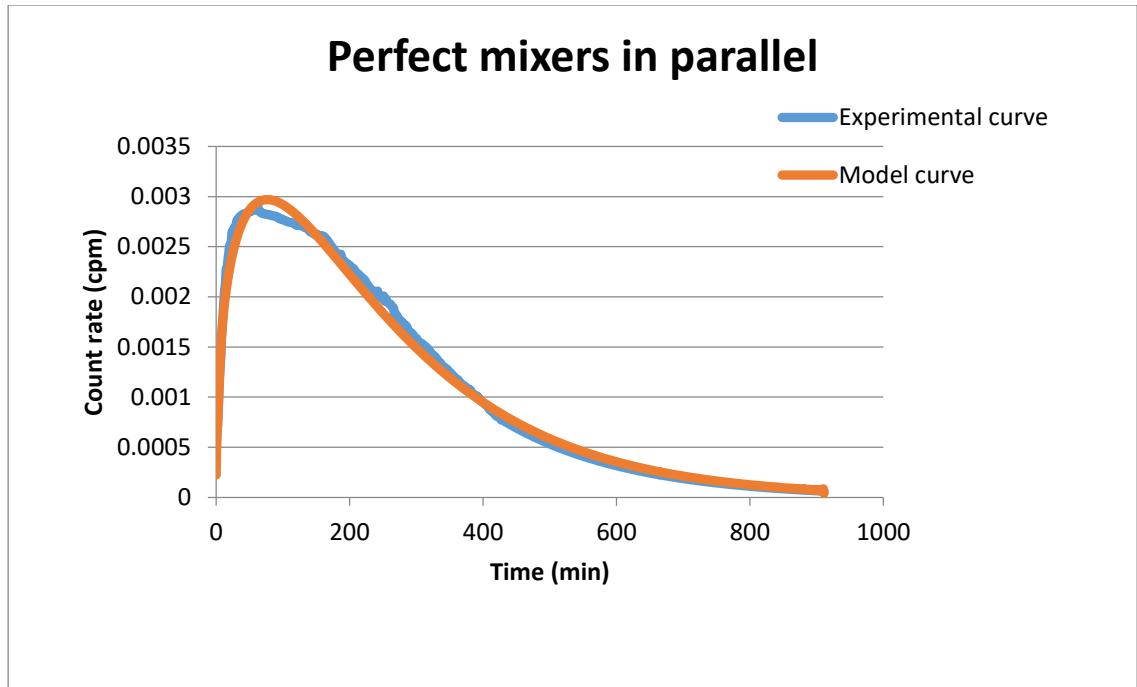


Figure 4.3 Perfect mixers in parallel model

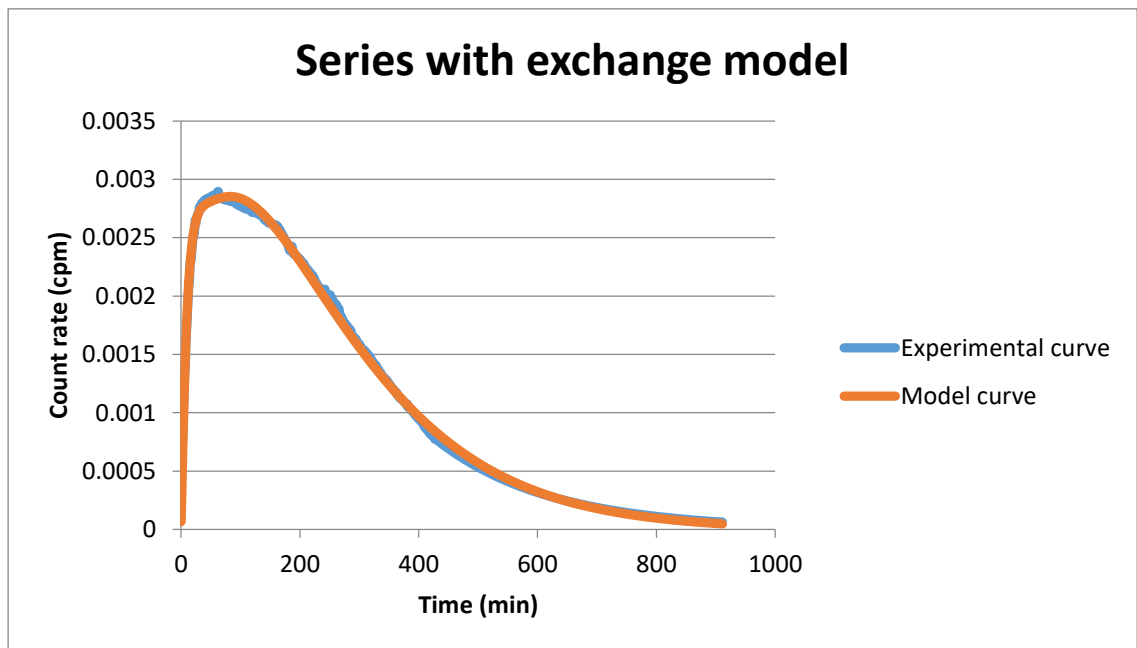


Figure 4.4 PMSE model fit

Table 4.2 Simulation parameters for perfect mixers in series with exchange model

Parameters	Optimal value of parameters
$\tau(\text{min})$	106.22
J	2.12
$T_m(\text{min})$	32.491
K	1.258

$$\text{Total MRT} = \bar{t} = \tau(1 + k) = 239.8$$

4.3

4.4 DISCUSSIONS OF EXPERIMENTAL RESULTS

From Fig.4.1, the tracer distribution curve measured at the exit of the digester exhibits an exponential decay behavior typical of stirred tank reactors. However, it is observed, from Table 4.1 that the designed MRT far exceeds the corresponding experimental value.

The designed MRT of 35 hours implies that the organic matter should stay in the digester for about 35 hours for it to be properly degraded (reduction in solid content) before moving to the settling tank. However, from the experimental result, the organic matter gets to the settling tank after staying in the digester for only 4 hours. This implies that material in the digester leave faster than expected and hence the organic matter is not being properly degraded before moving to the settling tank. In other words, the aerobic digestion process was not efficient.

For normal operating stirred tanks the effective working volume is about 80%. The remaining 20% accounts for the volume occupied by the agitator unit and other internal

features. The experimental results show that only 11.4% of the total volume is being used in the treatment process.

The remaining volume is therefore dead and not engaged in the digestion process. This means that the organic matter in this dead volume is not treated before settling.

The relatively low mean residence time and effective volume clearly show that the digester, as designed by personnel of the plant, is not efficient. This, to a greater extent, is due to flaws in design. These results were presented to plant personnel who confirmed that the unit as designed was not working properly and were going to replace the air diffusers and employ more vigorous agitation.

Modeling of the experimental data showed that the perfect mixers-in-series with exchange (PMSE) model provided the best fit and therefore the most suitable model to describe the flow structure in the digester. The model's MRT (from Table 4.2) of 3.9 hours is in good agreement with the experimental MRT of 4 hours as calculated from the method of moments.

The model suggests the presence of parallel flows in the digester and also confirms the presence of active and dead zones that exchange their flows.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The residence time distribution approach was used to evaluate the hydrodynamic parameters of the aerobic digester of a waste water treatment plant. The following conclusions are drawn from the study:

- The tracer distribution curve (RTD) measured at the exit of the digester exhibited an exponential decay behavior typical of stirred tank reactors.
- The designed MRT far exceeded the experimental MRT. Thus the material in the digester leaves faster than expected. Therefore the sludge was not properly treated in the digester before moving to the settling tank.
- Only 11.4% of the total volume of the digester was effectively used in the treatment process. The rest of the volume was dead and materials stayed there without being treated before discharge.
- The relatively low mean residence time and effective volume clearly show that the digester, as designed by personnel of the plant, was not efficient.
- The perfect mixers-in-series with exchange model best described the flow structure in the digester. The model confirmed the presence of parallel flows and the presence of active and dead zones.

5.2 RECOMMENDATIONS

5.2.1 To Industry

- There is the need to modify the design of the digester
- Conduct similar tests in the other units of the plant to confirm design data

5.2.2. Further Research

- Conduct CFD visualization of the flow field in the digester for optimum design.

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APPENDICES

Appendices A : Treated data

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
0	0	29	208.9538462	58	223.8	117	214.0769	146	206.8
1	7.892307692	30	209.4461538	59	223.8562	118	214.0615	147	206.4
2	18.8	31	210.9538	90	219.3538	119	213.8462	148	206.2
3	31.67692308	32	211.5231	91	219.3385	120	213.5846	149	205.6
4	46.75384615	33	212.4308	92	219.2154	121	212.8923	150	205.2
5	56.06153846	34	215.8307692	93	219.0308	122	212.6923	151	205.1
6	67.41538462	35	215.8462	94	218.8462	123	212.2	152	205
7	82.18461538	36	216.1231	95	218.2154	124	212.1	153	205
8	93.27692308	37	217.6307692	96	218.0308	125	212	154	205
9	103.5076923	38	218.5538	97	217.9385	126	212	155	205
10	109.4153846	39	218.9077	98	217.3077	127	212	156	204.6
11	125.0769231	40	219.3385	99	217	128	212	157	204.2
12	132.0153846	41	219.4769	100	216.9846	129	212	158	204.1
13	140.0769231	42	220.2308	101	216.9846	130	212	159	204
14	148.6	43	220.6462	102	216.9385	131	212	160	204
15	156.8	44	220.8923	103	216.3077	132	211.6154	161	204
16	162.7538462	45	220.9385	104	216.2	133	211.2	162	204
17	167.0461538	46	221.1077	105	215.9692	134	211	163	203.6
18	177.7846154	47	221.5077	106	215.8462	135	210.6	164	203.2
19	179.0615385	48	221.7231	107	215.7538	136	210.4	165	203.1
20	181.6615385	49	221.8154	108	215.4154	137	210.2	166	202.2
21	186.9384615	50	221.9077	109	215.0462	138	210	167	202
22	190.8153846	51	221.9846	110	214.9231	139	210	168	201
23	196.2461538	52	222	111	214.7231	140	210	169	200.03
24	196.5230769	53	222.7077	112	214.6308	141	209.7692	170	200.0269
25	197.7384615	54	222.8308	113	214.4462	142	208.3077	171	199.2715
26	201.7692308	55	223.0615	114	214.3538	143	207.7077	172	198.5215
27	207.2923077	56	223.2308	115	214.3385	144	207	173	197.7738
28	205.0153846	57	223.7077	116	214.1538	145	207	174	197.0308

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
175	196.2908	204	180.324	233	162.678	262	151.234	291	129.567
176	195.5562	205	179.654	234	162.256	263	150.89	292	129.432
177	194.8246	206	179.145	235	162	264	150.653	293	129.12
178	194.0969	207	178.987	236	161.786	265	150	294	128.564
179	193.3738	208	178.578	237	161.543	266	148.98	295	128.3
180	192.6523	209	178.234	238	161.21	267	148.54	296	127.987
181	191.9377	210	177.567	239	160	268	147.67	297	127.453
182	191.2231	211	176.43	240	158.678	269	147.43	298	126.89
183	190.5146	212	175.876	241	158.897	270	143.34	299	125.876
184	188.6307692	213	175.367	242	157.125	271	143.123	300	125.234
185	187.9846154	214	174.567	243	157.896	272	142.56	301	124.876
186	186.6	215	174.234	244	159.678	273	142.3	302	124.347
187	186.5538462	216	173.987	245	160.87	274	140.689	303	123.987
188	188.5538462	217	173.543	246	157	275	140.54	304	123.543
189	189.4769231	218	172.678	247	156.8765	276	139.567	305	121.789
190	189.3538462	219	172.538	248	156.98	277	138.587	306	121.453
191	185.2615385	220	171.876	249	156.365	278	138.234	307	121.23
192	185.8923077	221	171.489	250	155.875	279	137.897	308	120.798
193	184.238	222	171	251	155.456	280	137.567	309	120.457
194	184.1789	223	170.678	252	154.87	281	136.876	310	120
195	183.896	224	170	253	154.98	282	136	311	119.987
196	183.672	225	169.678	254	157	283	135.768	312	119.675
197	183.276	226	169	255	153.568	284	135.432	313	119.234
198	182.786	227	167.897	256	153.123	285	134.765	314	118.654
199	182.3456	228	167.365	257	154.89	286	134.432	315	118.231
200	181.897	229	165.9876	258	152.89	287	134.123	316	117.8765
201	181.347	230	165.4567	259	152.67	288	133.456	317	117.5673
202	181	231	164.67	260	152.2	289	132.789	318	116.456
203	180.987	232	164.276	261	151.67	290	130.678	319	116.245

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
320	115.768	349	99.98	378	85.678	407	72.123	436	59.111
321	115.432	350	99.453	379	85.123	408	71.98	437	58.80338462
322	114.789	351	98.632	380	84.658	409	71.654	438	58.49730769
323	113.543	352	98.124	381	84.32	410	70.89	439	58.19284615
324	113.214	353	97.542	382	84.1	411	70.321	440	57.89007692
325	111.789	354	97.21	383	82.78	412	69	441	57.58869231
326	111.678	355	96.67	384	83.78	413	68.89	442	57.289
327	111.128	356	95.76	385	82.43	414	68.532	443	56.99084615
328	110.987	357	95.34	386	81.67	415	67.43	444	56.69430769
329	110.452	358	94.98	387	81.25	416	67.12	445	56.39915385
330	110.056	359	94.21	388	80.87	417	67	446	56.10576923
331	109.89	360	93.876	389	80.453	418	66.432	447	55.81361538
332	108.897	361	93.41	390	80.12	419	65.99	448	55.52323077
333	108.349	362	92.6789	391	79.67	420	65.432	449	55.23423077
334	107.832	363	92.25	392	79.32	421	64.432	450	54.947
335	106.349	364	92.1	393	79	422	64.123	451	54.661
336	106.126	365	91.89	394	78.982	423	63.998	452	54.37630769
337	105.764	366	91.256	395	78.432	424	63.234	453	54.09338462
338	105.234	367	90	396	76.84	425	63.19	454	53.81184615
339	104.875	368	89.678	397	77.34	426	62.765	455	53.53176923
340	104	369	89.21	398	76.321	427	62.347	456	53.25315385
341	102.9876	370	88.543	399	75.876	428	61.897	457	52.976
342	102.467	371	88.43	400	75.345	429	61.34	458	52.70030769
343	102.123	372	87.69	401	74.74	430	60.45	459	52.426
344	101.678	373	87.276	402	74.234	431	60.234	460	52.15315385
345	101.543	374	87.1	403	73.9	432	60.18	461	51.88176923
346	101.12	375	86.876	404	73.65	433	60.04353846	462	51.61176923
347	100.543	376	86.432	405	73.12	434	59.731	463	51.34315385
348	100.213	377	86	406	72.67	435	59.42030769	464	51.07576923

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
465	50.81015385	494	43.67484615	523	37.54161538	552	32.26984615	581	27.73807692
466	50.54569231	495	43.44753846	524	37.346	553	32.10161538	582	27.59369231
467	50.28269231	496	43.22138462	525	37.15184615	554	31.93469231	583	27.45
468	50.021	497	42.99646154	526	36.95853846	555	31.76838462	584	27.30707692
469	49.76061538	498	42.77276923	527	36.76615385	556	31.60307692	585	27.16523077
470	49.50153846	499	42.55015385	528	36.57476923	557	31.43869231	586	27.02376923
471	49.24392308	500	42.329	529	36.38453846	558	31.275	587	26.88307692
472	48.98769231	501	42.10838462	530	36.19523077	559	31.11223077	588	26.74323077
473	48.73276923	502	41.88915385	531	36.00684615	560	30.95038462	589	26.604
474	48.47907692	503	41.67123077	532	35.81938462	561	30.78930769	590	26.46553846
475	48.22676923	504	41.45438462	533	35.63292308	562	30.62907692	591	26.32784615
476	47.97584615	505	41.23853846	534	35.44746154	563	30.46969231	592	26.19076923
477	47.72615385	506	41.02392308	535	35.263	564	30.31107692	593	26.05446154
478	47.47784615	507	40.81046154	536	35.07946154	565	30.15330769	594	25.91892308
479	47.23076923	508	40.59807692	537	34.897	566	29.99623077	595	25.784
480	46.98484615	509	40.38684615	538	34.71523077	567	29.84	596	25.64976923
481	46.74038462	510	40.17653846	539	34.53461538	568	29.68507692	597	25.51638462
482	46.497	511	39.96746154	540	34.35492308	569	29.53046154	598	25.38346154
483	46.25507692	512	39.75938462	541	34.17615385	570	29.37684615	599	25.25146154
484	46.01430769	513	39.55253846	542	33.99823077	571	29.22392308	600	25.12007692
485	45.77484615	514	39.34676923	543	33.82130769	572	29.07169231	601	24.989
486	45.53661538	515	39.14192308	544	33.64523077	573	28.92046154	602	24.859
487	45.29969231	516	38.93823077	545	33.47015385	574	28.76992308	603	24.72984615
488	45.06384615	517	38.73553846	546	33.296	575	28.62023077	604	24.60115385
489	44.829	518	38.53392308	547	33.12276923	576	28.47130769	605	24.47307692
490	44.59615385	519	38.33346154	548	32.95030769	577	28.32307692	606	24.34569231
491	44.364	520	38.134	549	32.77876923	578	28.17569231	607	24.219
492	44.13307692	521	37.93546154	550	32.60823077	579	28.02915385	608	24.093
493	43.90338462	522	37.738	551	32.43846154	580	27.88315385	609	23.96761538

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
610	23.84284615	639	20.49469231	668	17.61653846	697	15.14269231	726	13.01623077
611	23.71876923	640	20.38792308	669	17.525	698	15.064	727	12.94838462
612	23.59530769	641	20.28184615	670	17.434	699	14.98538462	728	12.88107692
613	23.47246154	642	20.17630769	671	17.343	700	14.90738462	729	12.814
614	23.35038462	643	20.07123077	672	17.25269231	701	14.83	730	12.74738462
615	23.22876923	644	19.967	673	17.16284615	702	14.75269231	731	12.681
616	23.10792308	645	19.863	674	17.07353846	703	14.676	732	12.615
617	22.98769231	646	19.75953846	675	16.98476923	704	14.59953846	733	12.54923077
618	22.868	647	19.65661538	676	16.89630769	705	14.52361538	734	12.484
619	22.74907692	648	19.55446154	677	16.80838462	706	14.448	735	12.419
620	22.63061538	649	19.45269231	678	16.72084615	707	14.37276923	736	12.35438462
621	22.513	650	19.35138462	679	16.634	708	14.298	737	12.29007692
622	22.396	651	19.25061538	680	16.54730769	709	14.22353846	738	12.22623077
623	22.27907692	652	19.15046154	681	16.46123077	710	14.14969231	739	12.16253846
624	22.16323077	653	19.05084615	682	16.37553846	711	14.076	740	12.09930769
625	22.04784615	654	18.95161538	683	16.29030769	712	14.00269231	741	12.03623077
626	21.933	655	18.853	684	16.20569231	713	13.92976923	742	11.97369231
627	21.81892308	656	18.75484615	685	16.12123077	714	13.85730769	743	11.91130769
628	21.70546154	657	18.65723077	686	16.03730769	715	13.78523077	744	11.84938462
629	21.59230769	658	18.56023077	687	15.95376923	716	13.71323077	745	11.78761538
630	21.48007692	659	18.46361538	688	15.87084615	717	13.64207692	746	11.72630769
631	21.36830769	660	18.36753846	689	15.78830769	718	13.571	747	11.66530769
632	21.257	661	18.272	690	15.70607692	719	13.50046154	748	11.60469231
633	21.14630769	662	18.17684615	691	15.62430769	720	13.43023077	749	11.54415385
634	21.03638462	663	18.08223077	692	15.54292308	721	13.36023077	750	11.48407692
635	20.92684615	664	17.98807692	693	15.462	722	13.29069231	751	11.42430769
636	20.818	665	17.89446154	694	15.38161538	723	13.22153846	752	11.36492308
637	20.70969231	666	17.80146154	695	15.30153846	724	13.15269231	753	11.30576923
638	20.60184615	667	17.70869231	696	15.22184615	725	13.08438462	754	11.24676923

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
755	11.18823077	784	9.617184615	813	8.266653846	842	7.105776923	871	6.107923077
756	11.13015385	785	9.567123077	814	8.2236	843	7.068784615	872	6.076123077
757	11.07223077	786	9.517353846	815	8.180830769	844	7.032	873	6.0445
758	11.01453846	787	9.4678	816	8.138246154	845	6.995407692	874	6.013046154
759	10.95723077	788	9.418530769	817	8.095892308	846	6.959	875	5.981746154
760	10.90015385	789	9.369515385	818	8.053769231	847	6.922784615	876	5.950630769
761	10.84346154	790	9.320753846	819	8.011853846	848	6.886746154	877	5.919646154
762	10.787	791	9.272246154	820	7.970146154	849	6.850923077	878	5.888838462
763	10.73092308	792	9.224	821	7.928669231	850	6.815253846	879	5.858184615
764	10.67507692	793	9.175984615	822	7.8874	851	6.779784615	880	5.8277
765	10.61953846	794	9.128230769	823	7.846369231	852	6.744507692	881	5.797369231
766	10.56423077	795	9.080730769	824	7.805515385	853	6.709407692	882	5.7672
767	10.50923077	796	9.033461538	825	7.764892308	854	6.674484615	883	5.7372
768	10.45461538	797	8.986438462	826	7.7245	855	6.639738462	884	5.707330769
769	10.40015385	798	8.939669231	827	7.684276923	856	6.605176923	885	5.677623077
770	10.346	799	8.893146154	828	7.6443	857	6.570807692	886	5.648069231
771	10.29223077	800	8.846876923	829	7.604507692	858	6.536615385	887	5.618684615
772	10.23861538	801	8.800823077	830	7.564938462	859	6.502607692	888	5.589438462
773	10.18538462	802	8.755030769	831	7.525569231	860	6.468738462	889	5.560353846
774	10.13230769	803	8.709446154	832	7.4864	861	6.435084615	890	5.5314
775	10.07969231	804	8.664123077	833	7.447430769	862	6.4016	891	5.502623077
776	10.027	805	8.619030769	834	7.408661538	863	6.368284615	892	5.474
777	9.974953846	806	8.574176923	835	7.370107692	864	6.335138462	893	5.4455
778	9.923046154	807	8.529553846	836	7.331753846	865	6.302169231	894	5.417161538
779	9.8714	808	8.485161538	837	7.293592308	866	6.269369231	895	5.388976923
780	9.820023077	809	8.441015385	838	7.255638462	867	6.236723077	896	5.360923077
781	9.768915385	810	8.397076923	839	7.2179	868	6.204269231	897	5.333023077
782	9.7181	811	8.353376923	840	7.180307692	869	6.171992308	898	5.305253846
783	9.6675	812	8.3099	841	7.142946154	870	6.139876923	899	5.277646154

Appendice B : Normalized data

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
0	0	30	0.0026798	60	0.0028659	90	0.0028066	120	0.0027328
1	0.00010098	31	0.0026991	61	0.0028661	91	0.0028064	121	0.0027239
2	0.00024054	32	0.0027064	62	0.0028696	92	0.0028048	122	0.0027214
3	0.0004053	33	0.002718	63	0.0028729	93	0.0028025	123	0.0027151
4	0.00059821	34	0.0027615	64	0.0028813	94	0.0028001	124	0.0027138
5	0.0007173	35	0.0027617	65	0.0028946	95	0.002792	125	0.0027125
6	0.00086257	36	0.0027653	66	0.0028873	96	0.0027897	126	0.0027125
7	0.0010515	37	0.0027846	67	0.002859	97	0.0027885	127	0.0027125
8	0.0011935	38	0.0027964	68	0.0028503	98	0.0027804	128	0.0027125
9	0.0013244	39	0.0028009	69	0.0028477	99	0.0027765	129	0.0027125
10	0.0014	40	0.0028064	70	0.0028428	100	0.0027763	130	0.0027125
11	0.0016003	41	0.0028082	71	0.0028367	101	0.0027763	131	0.0027125
12	0.0016891	42	0.0028178	72	0.0028344	102	0.0027757	132	0.0027076
13	0.0017923	43	0.0028231	73	0.0028336	103	0.0027676	133	0.0027023
14	0.0019013	44	0.0028263	74	0.0028294	104	0.0027663	134	0.0026997
15	0.0020062	45	0.0028269	75	0.0028294	105	0.0027633	135	0.0026946
16	0.0020824	46	0.002829	76	0.0028249	106	0.0027617	136	0.002692
17	0.0021373	47	0.0028342	77	0.0028245	107	0.0027605	137	0.0026895
18	0.0022747	48	0.0028369	78	0.0028231	108	0.0027562	138	0.0026869
19	0.0022911	49	0.0028381	79	0.0028231	109	0.0027515	139	0.0026869
20	0.0023243	50	0.0028393	80	0.002822	110	0.0027499	140	0.0026869
21	0.0023919	51	0.0028403	81	0.002822	111	0.0027474	141	0.002684
22	0.0024415	52	0.0028405	82	0.0028202	112	0.0027462	142	0.0026653
23	0.0025109	53	0.0028495	83	0.0028186	113	0.0027438	143	0.0026576
24	0.0025145	54	0.0028511	84	0.0028131	114	0.0027426	144	0.0026485
25	0.00253	55	0.002854	85	0.0028127	115	0.0027424	145	0.0026485
26	0.0025816	56	0.0028562	86	0.0028113	116	0.0027401	146	0.002646
27	0.0026523	57	0.0028623	87	0.00281	117	0.0027391	147	0.0026409
28	0.0026231	58	0.0028635	88	0.0028094	118	0.0027389	148	0.0026383
29	0.0026735	59	0.0028642	89	0.0028068	119	0.0027361	149	0.0026306

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
150	0.0026255	181	0.0024558	212	0.0022503	243	0.0020203	274	0.0018001
151	0.0026242	182	0.0024467	213	0.0022438	244	0.0020431	275	0.0017982
152	0.0026229	183	0.0024376	214	0.0022336	245	0.0020583	276	0.0017857
153	0.0026229	184	0.0024135	215	0.0022293	246	0.0020088	277	0.0017732
154	0.0026229	185	0.0024052	216	0.0022261	247	0.0020072	278	0.0017687
155	0.0026229	186	0.0023875	217	0.0022205	248	0.0020085	279	0.0017644
156	0.0026178	187	0.0023869	218	0.0022094	249	0.0020007	280	0.0017602
157	0.0026127	188	0.0024125	219	0.0022076	250	0.0019944	281	0.0017513
158	0.0026114	189	0.0024243	220	0.0021991	251	0.001989	282	0.0017401
159	0.0026102	190	0.0024228	221	0.0021942	252	0.0019815	283	0.0017371
160	0.0026102	191	0.0023704	222	0.0021879	253	0.001983	284	0.0017328
161	0.0026102	192	0.0023785	223	0.0021838	254	0.0020088	285	0.0017243
162	0.0026102	193	0.0023573	224	0.0021751	255	0.0019649	286	0.00172
163	0.002605	194	0.0023565	225	0.002171	256	0.0019592	287	0.0017161
164	0.0025999	195	0.0023529	226	0.0021623	257	0.0019818	288	0.0017076
165	0.0025986	196	0.0023501	227	0.0021482	258	0.0019562	289	0.001699
166	0.0025871	197	0.002345	228	0.0021414	259	0.0019534	290	0.001672
167	0.0025846	198	0.0023387	229	0.0021238	260	0.0019474	291	0.0016578
168	0.0025718	199	0.0023331	230	0.002117	261	0.0019406	292	0.0016561
169	0.0025594	200	0.0023273	231	0.0021069	262	0.001935	293	0.0016521
170	0.0025593	201	0.0023203	232	0.0021019	263	0.0019306	294	0.001645
171	0.0025497	202	0.0023159	233	0.0020814	264	0.0019276	295	0.0016416
172	0.0025401	203	0.0023157	234	0.002076	265	0.0019192	296	0.0016376
173	0.0025305	204	0.0023072	235	0.0020728	266	0.0019062	297	0.0016307
174	0.002521	205	0.0022987	236	0.00207	267	0.0019006	298	0.0016235
175	0.0025115	206	0.0022921	237	0.0020669	268	0.0018894	299	0.0016106
176	0.0025021	207	0.0022901	238	0.0020627	269	0.0018863	300	0.0016024
177	0.0024928	208	0.0022849	239	0.0020472	270	0.001834	301	0.0015978
178	0.0024834	209	0.0022805	240	0.0020303	271	0.0018312	302	0.001591
179	0.0024742	210	0.0022719	241	0.0020331	272	0.001824	303	0.0015864
180	0.002465	211	0.0022574	242	0.0020104	273	0.0018207	304	0.0015807

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
305	0.0015583	336	0.0013579	367	0.0011515	398	0.00097652	429	0.00078484
306	0.001554	337	0.0013532	368	0.0011474	399	0.00097082	430	0.00077345
307	0.0015511	338	0.0013465	369	0.0011414	400	0.00096403	431	0.00077069
308	0.0015456	339	0.0013419	370	0.0011329	401	0.00095629	432	0.00077
309	0.0015412	340	0.0013307	371	0.0011315	402	0.00094981	433	0.00076825
310	0.0015354	341	0.0013177	372	0.001122	403	0.00094554	434	0.00076425
311	0.0015352	342	0.0013111	373	0.0011167	404	0.00094234	435	0.00076028
312	0.0015312	343	0.0013067	374	0.0011144	405	0.00093556	436	0.00075632
313	0.0015256	344	0.001301	375	0.0011116	406	0.0009298	437	0.00075238
314	0.0015182	345	0.0012992	376	0.0011059	407	0.0009228	438	0.00074847
315	0.0015128	346	0.0012938	377	0.0011004	408	0.00092098	439	0.00074457
316	0.0015082	347	0.0012864	378	0.0010962	409	0.0009168	440	0.0007407
317	0.0015043	348	0.0012822	379	0.0010891	410	0.00090703	441	0.00073684
318	0.00149	349	0.0012792	380	0.0010832	411	0.00089975	442	0.00073301
319	0.0014873	350	0.0012725	381	0.0010789	412	0.00088285	443	0.00072919
320	0.0014812	351	0.001262	382	0.001076	413	0.00088144	444	0.0007254
321	0.0014769	352	0.0012555	383	0.0010592	414	0.00087686	445	0.00072162
322	0.0014687	353	0.001248	384	0.001072	415	0.00086276	446	0.00071787
323	0.0014528	354	0.0012438	385	0.0010547	416	0.00085879	447	0.00071413
324	0.0014486	355	0.0012369	386	0.001045	417	0.00085726	448	0.00071041
325	0.0014303	356	0.0012252	387	0.0010396	418	0.00084999	449	0.00070672
326	0.0014289	357	0.0012199	388	0.0010347	419	0.00084433	450	0.00070304
327	0.0014219	358	0.0012153	389	0.0010294	420	0.00083719	451	0.00069938
328	0.0014201	359	0.0012054	390	0.0010251	421	0.0008244	452	0.00069574
329	0.0014132	360	0.0012011	391	0.0010194	422	0.00082045	453	0.00069212
330	0.0014082	361	0.0011952	392	0.0010149	423	0.00081885	454	0.00068852
331	0.001406	362	0.0011858	393	0.0010108	424	0.00080907	455	0.00068493
332	0.0013933	363	0.0011803	394	0.0010106	425	0.00080851	456	0.00068137
333	0.0013863	364	0.0011784	395	0.0010035	426	0.00080307	457	0.00067782
334	0.0013797	365	0.0011757	396	0.00098316	427	0.00079772	458	0.00067429
335	0.0013607	366	0.0011676	397	0.00098956	428	0.00079196	459	0.00067078

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
460	0.00066729	491	0.00056763	522	0.00048285	553	0.00041074	584	0.00034939
461	0.00066382	492	0.00056468	523	0.00048034	554	0.0004086	585	0.00034758
462	0.00066037	493	0.00056174	524	0.00047784	555	0.00040647	586	0.00034577
463	0.00065693	494	0.00055881	525	0.00047535	556	0.00040436	587	0.00034397
464	0.00065351	495	0.00055591	526	0.00047288	557	0.00040225	588	0.00034218
465	0.00065011	496	0.00055301	527	0.00047042	558	0.00040016	589	0.00034039
466	0.00064673	497	0.00055013	528	0.00046797	559	0.00039808	590	0.00033862
467	0.00064336	498	0.00054727	529	0.00046554	560	0.00039601	591	0.00033686
468	0.00064001	499	0.00054442	530	0.00046311	561	0.00039395	592	0.00033511
469	0.00063668	500	0.00054159	531	0.0004607	562	0.0003919	593	0.00033336
470	0.00063337	501	0.00053877	532	0.0004583	563	0.00038986	594	0.00033163
471	0.00063007	502	0.00053597	533	0.00045592	564	0.00038783	595	0.0003299
472	0.00062679	503	0.00053318	534	0.00045355	565	0.00038581	596	0.00032819
473	0.00062353	504	0.0005304	535	0.00045119	566	0.0003838	597	0.00032648
474	0.00062028	505	0.00052764	536	0.00044884	567	0.0003818	598	0.00032478
475	0.00061706	506	0.0005249	537	0.0004465	568	0.00037982	599	0.00032309
476	0.00061385	507	0.00052216	538	0.00044418	569	0.00037784	600	0.00032141
477	0.00061065	508	0.00051945	539	0.00044187	570	0.00037587	601	0.00031973
478	0.00060747	509	0.00051674	540	0.00043957	571	0.00037392	602	0.00031807
479	0.00060431	510	0.00051405	541	0.00043728	572	0.00037197	603	0.00031642
480	0.00060117	511	0.00051138	542	0.000435	573	0.00037003	604	0.00031477
481	0.00059804	512	0.00050872	543	0.00043274	574	0.00036811	605	0.00031313
482	0.00059492	513	0.00050607	544	0.00043049	575	0.00036619	606	0.0003115
483	0.00059183	514	0.00050344	545	0.00042825	576	0.00036429	607	0.00030988
484	0.00058875	515	0.00050082	546	0.00042602	577	0.00036239	608	0.00030827
485	0.00058568	516	0.00049821	547	0.0004238	578	0.0003605	609	0.00030666
486	0.00058264	517	0.00049562	548	0.0004216	579	0.00035863	610	0.00030507
487	0.0005796	518	0.00049304	549	0.0004194	580	0.00035676	611	0.00030348
488	0.00057659	519	0.00049047	550	0.00041722	581	0.00035491	612	0.0003019
489	0.00057358	520	0.00048792	551	0.00041505	582	0.00035306	613	0.00030033
490	0.0005706	521	0.00048538	552	0.00041289	583	0.00035122	614	0.00029877

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
615	0.00029721	646	0.00025282	677	0.00021506	708	0.00018294	739	0.00015562
616	0.00029566	647	0.0002515	678	0.00021394	709	0.00018199	740	0.00015481
617	0.00029412	648	0.0002502	679	0.00021283	710	0.00018104	741	0.000154
618	0.00029259	649	0.00024889	680	0.00021172	711	0.0001801	742	0.0001532
619	0.00029107	650	0.0002476	681	0.00021062	712	0.00017916	743	0.0001524
620	0.00028956	651	0.00024631	682	0.00020952	713	0.00017823	744	0.00015161
621	0.00028805	652	0.00024503	683	0.00020843	714	0.0001773	745	0.00015082
622	0.00028655	653	0.00024375	684	0.00020735	715	0.00017638	746	0.00015004
623	0.00028506	654	0.00024248	685	0.00020627	716	0.00017546	747	0.00014926
624	0.00028358	655	0.00024122	686	0.0002052	717	0.00017455	748	0.00014848
625	0.0002821	656	0.00023997	687	0.00020413	718	0.00017364	749	0.00014771
626	0.00028063	657	0.00023872	688	0.00020307	719	0.00017274	750	0.00014694
627	0.00027917	658	0.00023748	689	0.00020201	720	0.00017184	751	0.00014617
628	0.00027772	659	0.00023624	690	0.00020096	721	0.00017094	752	0.00014541
629	0.00027627	660	0.00023501	691	0.00019991	722	0.00017005	753	0.00014466
630	0.00027483	661	0.00023379	692	0.00019887	723	0.00016917	754	0.0001439
631	0.0002734	662	0.00023257	693	0.00019783	724	0.00016829	755	0.00014315
632	0.00027198	663	0.00023136	694	0.00019681	725	0.00016741	756	0.00014241
633	0.00027056	664	0.00023016	695	0.00019578	726	0.00016654	757	0.00014167
634	0.00026916	665	0.00022896	696	0.00019476	727	0.00016567	758	0.00014093
635	0.00026776	666	0.00022777	697	0.00019375	728	0.00016481	759	0.0001402
636	0.00026636	667	0.00022658	698	0.00019274	729	0.00016395	760	0.00013947
637	0.00026498	668	0.0002254	699	0.00019174	730	0.0001631	761	0.00013874
638	0.0002636	669	0.00022423	700	0.00019074	731	0.00016225	762	0.00013802
639	0.00026223	670	0.00022307	701	0.00018975	732	0.00016141	763	0.0001373
640	0.00026086	671	0.0002219	702	0.00018876	733	0.00016057	764	0.00013659
641	0.0002595	672	0.00022075	703	0.00018778	734	0.00015973	765	0.00013588
642	0.00025815	673	0.0002196	704	0.0001868	735	0.0001589	766	0.00013517
643	0.00025681	674	0.00021845	705	0.00018583	736	0.00015807	767	0.00013446
644	0.00025548	675	0.00021732	706	0.00018486	737	0.00015725	768	0.00013377
645	0.00025414	676	0.00021619	707	0.0001839	738	0.00015643	769	0.00013307

Time	Data	Time	Data	Time	Data	Time	Data	Time	Data
770	0.00013238	801	0.00011261	832	9.58E-05	863	8.15E-05	894	6.93E-05
771	0.00013169	802	0.00011202	833	9.53E-05	864	8.11E-05	895	6.90E-05
772	0.000131	803	0.00011144	834	9.48E-05	865	8.06E-05	896	6.86E-05
773	0.00013032	804	0.00011086	835	9.43E-05	866	8.02E-05	897	6.82E-05
774	0.00012964	805	0.00011028	836	9.38E-05	867	7.98E-05	898	6.79E-05
775	0.00012897	806	0.00010971	837	9.33E-05	868	7.94E-05	899	6.75E-05
776	0.00012829	807	0.00010913	838	9.28E-05	869	7.90E-05	900	6.72E-05
777	0.00012763	808	0.00010857	839	9.24E-05	870	7.86E-05	901	6.68E-05
778	0.00012696	809	0.000108	840	9.19E-05	871	7.82E-05	902	6.65E-05
779	0.0001263	810	0.00010744	841	9.14E-05	872	7.77E-05	903	6.61E-05
780	0.00012565	811	0.00010688	842	9.09E-05	873	7.73E-05	904	6.58E-05
781	0.00012499	812	0.00010632	843	9.04E-05	874	7.69E-05	905	6.54E-05
782	0.00012434	813	0.00010577	844	9.00E-05	875	7.65E-05	906	6.51E-05
783	0.00012369	814	0.00010522	845	8.95E-05	876	7.61E-05	907	6.48E-05
784	0.00012305	815	0.00010467	846	8.90E-05	877	7.57E-05	908	6.44E-05
785	0.00012241	816	0.00010413	847	8.86E-05	878	7.53E-05	909	6.41E-05
786	0.00012177	817	0.00010359	848	8.81E-05	879	7.50E-05	910	6.38E-05
787	0.00012114	818	0.00010305	849	8.77E-05	880	7.46E-05	911	6.34E-05
788	0.00012051	819	0.00010251	850	8.72E-05	881	7.42E-05	912	6.31E-05
789	0.00011988	820	0.00010198	851	8.67E-05	882	7.38E-05	913	6.28E-05
790	0.00011926	821	0.00010145	852	8.63E-05	883	7.34E-05	914	6.24E-05
791	0.00011864	822	0.00010092	853	8.58E-05	884	7.30E-05	915	6.21E-05
792	0.00011802	823	0.00010039	854	8.54E-05	885	7.26E-05		
793	0.00011741	824	9.99E-05	855	8.50E-05	886	7.23E-05		
794	0.00011679	825	9.94E-05	856	8.45E-05	887	7.19E-05		
795	0.00011619	826	9.88E-05	857	8.41E-05	888	7.15E-05		
796	0.00011558	827	9.83E-05	858	8.36E-05	889	7.11E-05		
797	0.00011498	828	9.78E-05	859	8.32E-05	890	7.08E-05		
798	0.00011438	829	9.73E-05	860	8.28E-05	891	7.04E-05		
799	0.00011379	830	9.68E-05	861	8.23E-05	892	7.00E-05		
800	0.00011319	831	9.63E-05	862	8.19E-05	893	6.97E-05		