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Radiotracer Applications in Wastewater Treatment Plants

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TRAINING COURSE SERIES 49

RADIOTRACER APPLICATIONS IN WASTEWATER TREATMENT PLANTS

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For further information on this publication, please contact:

Industrial Applications and Chemistry Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
email: Official.Mail@iaea.org

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TRAINING COURSE SERIES No. 49

RADIOTRACER APPLICATIONS IN WASTEWATER TREATMENT PLANTS

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2011

FOREWORD

Wastewater containing pollutants resulting from municipal and industrial activities are normally collected in wastewater treatment plants (WWTPs) for processing before discharge to the environment. The WWTPs are the last barrier against contamination of downstream surface waters such as rivers, lakes and sea. Treated wastewater is reused for irrigation, particularly in arid and semi-arid countries. Therefore, it is very important to maintain optimal operating conditions of WWTPs to eliminate or reduce environmental pollution.

Wastewater treatment plants are complicated systems, where the processes of mixing, separation, aeration, biological and chemical reactions occur. A WWTP is basically a multiphase system, and the efficiency of an installation strongly depends on liquid, solid and gas phase flow structures and their residence time distributions (RTDs). However, the fluid dynamic properties of such systems are not yet completely understood, rendering difficult the theoretical prediction of important process parameters such as flow rates, phase distributions, mixing and sediment characteristics.

Tracer techniques are very useful tools to investigate the efficiency of purification in WWTPs, aiding both their design and performance optimization. There are many kinds of tracers. Radioactive tracers are the most sensitive and are largely used for on-line diagnosis of various operations in WWTPs. The success of radiotracer applications rests upon their extremely high detection sensitivity, and the strong resistance against severe process conditions.

During the last few decades, many radiotracer studies have been conducted worldwide for investigation of various installations for wastewater treatment, such as mixer, aeration tank, clarifiers, digester, filter, wetland and oxidation units. Various radiotracer methods and techniques have been developed by individual tracer groups. However, the information necessary for the preservation of knowledge and transfer of technology to developing countries has not yet been compiled. Standard procedures or guidelines for the tracer experiments, vital for the reliability of the experiments as well as for the acceptance of end users, have also not been established by international tracer community.

The IAEA plays a major role in facilitating the transfer of radiotracer technology to developing Member States. The major radiotracer techniques have been implemented through IAEA technical cooperation projects. The sustainability of the technology and knowledge preservation calls for continuing human resource development and for establishing good practices. The education of specialists and continuous training of radiotracer practitioners is vital for the provision of quality services to environmental end users.

This publication was prepared using the inputs from a meeting of experts held in June 2007 and lecture materials prepared for various IAEA regional training courses. It is intended to assist radiotracer groups in Member States to promote and apply radiotracer technology for better serving the environmental sector.

The IAEA wishes to thank all of the contributors to this publication. The IAEA officers responsible for this publication were P.M. Dias and K. Sukasam of the Department of Technical Cooperation and J-H. Jin of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

CONTENTS

INTRODUCTION

With the advent of industrial growth, water as a resource is becoming a limiting commodity. This is due to the following two facts: distribution of available sources of usable water is unevenly spread out, and the discharge of the effluents on land and in the existing water bodies is deteriorating the quality of these sources for their possible exploitation.

The problems can be tackled on these two fronts simultaneously by (a) improving the main water, harvesting methodologies so that the precipitation is distributed more evenly for water usage, and (b) treating the used water in such a way that is does not significantly affect the water quality of the sources currently available. These two methods together can be considered important for water management. The wastewater management essentially addresses the second part of the strategy i.e. how effectively and efficiently one can treat the wastewater, so that it can be discharged without affecting the environment or can be recycled and reused.

Sewage treatment is a multi-stage process as shown in Fig.1. The purpose of wastewater treatment is to remove pollutants that can harm the aquatic environment if they are discharged into it. It includes physical, chemical and biological processes to reduce or remove organic matter, solids, nutrients, disease-causing organisms and other pollutants from wastewater. The site where the raw wastewater is processed before its discharge to the environment is called wastewater treatment plant (WWTP) or, less used, sewage treatment plant.

FIG.1. View of a typical WWTP.

The quality of the wastewater, the type and level of contamination existing in the source are widely different and hence the treatment strategy for each wastewater is significantly different. A WWTP is a multiphase system and the efficiency of an installation strongly depends on the liquid, solid and gas phase flow structures and their residence time distributions (RTD).

Tracer techniques are highly useful tools to investigate the efficiency of purification in wastewater treatment installations aiding both their design and performance optimization. The radiotracer (or radioactive tracers) are the most suitable for online diagnosis of various operations in WWTP, and are largely used in many countries.

The success of radiotracer applications rests upon: (1) the possibility of on-line measurement under operating condition without disruption of the processes in the plant, (2), the possibility to perform radiotracer experiments using such small amount of radioactive materials that labeled wastewater may be handled as non-radioactive waste, and (3) the strong resistance of radiotracers against the process conditions of WWTP.

By applying radiotracer techniques for the investigation of WWTP one can provide answers to the questions listed below:

- How is the inlet flow into the tanks distributed?
- Are there shortcut circuits between inlets and outlets?
- Are there any dead areas or stagnant zones in the tanks?
- At what distance from the mixer is mixture effective?
- What is the real shape of breakthrough curve?
- How long is the average retention time in the tank?
- Has the retention time an ideal distribution around the means?
- Is the retention time long enough for sanitation?
- How quick is the sedimentation?
- Are the sludge scrappers effective?
- Are there short circuits from the inlet area to the sludge pit?
- How great is the gas flow in the pipe system?

This Training Course Series (TCS) provides principle of operations and equipments used for the treatment of wastewater and theoretical and practical aspects of radiotracer technology as applied to WWTP, in particular it describes the possible role of radiotracers in accessing the variety of these treatments operations for their efficacy and optimization. The use of radiotracers for a variety of WWTP processes is illustrated with many case studies that show advantages and benefits of radiotracer applications in WWTP. This book is intended to serve the needs of:

- Radiotracer groups to promote and provide services of radiotracer techniques to environmental and industrial sectors,
- Graduate students of environmental and engineering faculties to expand their knowledge and to make use of radiotracer techniques in research and development,
- Engineers and managers of environmental sector to understand the potential of radiotracer techniques for investigating, better designing and optimizing the WWTP.

The first part (Section 1) illustrates various wastewater treatment technologies. Technical details on major treatment methods and processing units are presented. This part intends to introduce basic information on WWTP to radiotracer practitioners. Part two (Sections 2 and 3) provides basic knowledge on tracer technology to engineers of the WWTPs. Tracers and radiotracers for diagnosing WWTP units are introduced. Comparison of conventional and radiotracer techniques is developed, showing the advantages of radiotracers especially regarding their sensitivity, resistivity and selectivity. Radiotracer characteristics, selection and preparation of radiotracers, radiotracer detection, residence time distribution (RTD) function and its modeling are described as well. The integration of tracer RTD method with simulation by computer fluid dynamics (CFD) is introduced. Part three (Section 4) provides typical applications of radiotracer techniques for investigation of WWTP units and processes. It illustrates radiotracer methodology with many real case studies. The chosen applications represent the major problems of WWTP where the radiotracers are very competitive and sometimes unique to solve the problem. Encouraging utilization of radiotracers as most competitive for on-line and multitracer investigation in WWTP, the material presents also case studies where other tracers are used instead of radiotracers, mostly due to public acceptance and strict regulations in some countries. This part provides both to radiotracer service providers and end-users common points of cooperation for investigation and problem solving in different WWTP units and processes.

1. WASTEWATER TREATMENT TECHNOLOGIES

1.1. WASTEWATER TREATMENT PROCESSES

The typical contaminants in the domestic effluent are fecal discharges (containing E. coli and other microbes and nutrients in the form of ammonia, urea, etc.), dissolved and suspended solids, and dissolved gases (H_2S, NH_3, etc.). Similarly, typical contaminants in the industrial effluent are suspended and dissolved solids (inorganic, including heavy metals and organic), dissolved complex organic compounds, color bearing compounds (dyes and pigments) and dissolved gases. The main objective of the effluent treatment is to either decompose the contaminant into environmentally harmless products or to stabilize the contaminant into its most stable thermodynamic form. Various physical, chemical and biological methods are used to remove contaminants from wastewater, and therefore the wastewater processes can be classified as physical, chemical and biological unit operations.

1.1.1. Physical processes

Physical forces are applied to remove contaminants in physical unit operations. The physical process includes unit operations for screening, flow equalization, sedimentation, flotation and granular-medium filtration.

(a) Screening

Screening is the first physical operation carried out on the incoming effluent. It removes coarse particles and other floating rubbish materials such as plastic pieces, loose sheets and bags etc. This is achieved by allowing the wastewater to flow through the rakes or screens depending on the extent of large solids present in the incoming effluent. Particles larger than 10 mm are generally removed out this stage. Since, after this stage, the effluent is pumped using centrifugal pumps, the removal of large solids protect the subsequent pumping equipment. The material retained from the manual or mechanical cleaning of bar racks and screens is referred to as 'screenings', and is either disposed of by burial or incineration, or returned into the waste flow after grinding.

(b) Flow equalization

Flow equalization is a technique used to improve the effectiveness of wastewater treatment processes by leveling out operation parameters such as flow and pollutant levels over a period of time. Variations are damped until a near-constant flow rate is achieved, minimizing the downstream effects of these parameters.

(c) Sedimentation

Sedimentation, a fundamental and widely used unit operation in wastewater treatment, involves the gravitational settling of heavy particles suspended in a mixture. Sedimentation takes place in a settling tank, also referred to as a clarifier. This process is used for the removal of grit, particulate matter in the primary settling basin, as well as biological flocks in the activated sludge settling basin (or secondary clarifier).

(d) Flotation

Flotation is a unit operation used to remove solid particles from a liquid phase by introducing a fine gas, usually air bubbles. The gas bubbles either adhere to the liquid or are trapped in the particle structure of the suspended solids, raising the buoyant force of the combined particle and gas bubbles. Particles that have a higher density than the liquid can thus be made to rise. In wastewater treatment, flotation is used mainly to remove suspended matter and to concentrate biological sludge. The chief advantage of flotation over sedimentation is that very small or light particles can be removed more completely and in a shorter time. Once the particles have been floated to the surface, they can be skimmed out. Flotation, as currently practiced in WWTP, uses air exclusively as the floating agent. Furthermore, various chemical additives can be introduced to enhance the removal process.

(e) Granular medium filtration

The filtration of effluents is used for the supplemental removal of suspended solids. The wastewater to be filtered is passed through a filter bed consisting of granular material such as sand, and/or anthracite.

1.1.2. Chemical processes

Chemical processes used in wastewater treatment are designed to bring about some form of change by means of chemical reactions. They are always used in conjunction with physical unit operations and biological processes. The chemical process includes unit operations for chemical precipitation, adsorption, disinfection and dechlorination.

(a) Chemical precipitation

Chemical coagulation of raw wastewater before sedimentation promotes the flocculation of fine solids into more readily settleable flocks, thereby enhancing the efficiency of suspended solid removal as compared to plain sedimentation without coagulation. The degree of clarification obtained depends on the kind and quantity of coagulant used and the care with which the process is controlled. Coagulant selection for enhanced sedimentation is based on performance, reliability and cost.

(b) Disinfection

Disinfection refers to the selective destruction of disease-causing microorganisms. This process is of importance in wastewater treatment owing to the nature of wastewater, which harbors a number of human enteric organisms that are associated with various waterborne diseases. Commonly used means of disinfection include ultraviolet (UV) light, gamma ray or electron beam and various chemical agents. The most common chemical disinfectants are the oxidizing chemicals, and of these, chlorine is the most widely used.

1.1.3. Biological processes

Biological unit processes are used to convert the fine dissolved organic matter in wastewater into flocculent settleable solids. In these processes, micro-organisms, particularly bacteria, convert the colloidal and dissolved organic matter into various gases and into cell tissue which is then removed in sedimentation tanks. Biological processes are usually used in conjunction with physical and chemical processes. Biological processes used for wastewater treatment are activated sludge process, aerated lagoon, trickling filters, rotating biological contactors, pond stabilization, nutrient removal process and anaerobic digestion.

(a) Aerobic activated-sludge process

The activated-sludge process is an aerobic continuous-flow system containing a mass of activated microorganisms that are capable of stabilizing organic matter. Aeration basin is used for aerobic process. The aerobic environment is maintained in the aeration basin by means of diffused or mechanical aeration, which also serves to keep the contents of the reactor mixed. After a specific retention time, the mixed liquor passes into the secondary clarifier, where the sludge is allowed to settle and a clarified effluent is produced for discharge.

(b) Anaerobic digestion

Anaerobic digestion involves the biological conversion of organic matter in the absence of molecular oxygen to a variety of end-products including methane and carbon dioxide. The process takes place in an airtight reactor. Sludge is introduced continuously or intermittently and retained in the reactor for a period of time. Anaerobic digesters are commonly used for the treatment of sludge with high organic content. An advantage of this type of system is the production of methane gas, which can be used as a fuel.

1.2. APPLICATION OF WASTEWATER TREATMENT PROCESSES

Commonly there are various treatment levels in the wastewater treatment process; preliminary, primary, secondary and tertiary (or advanced) treatment (Fig. 2).

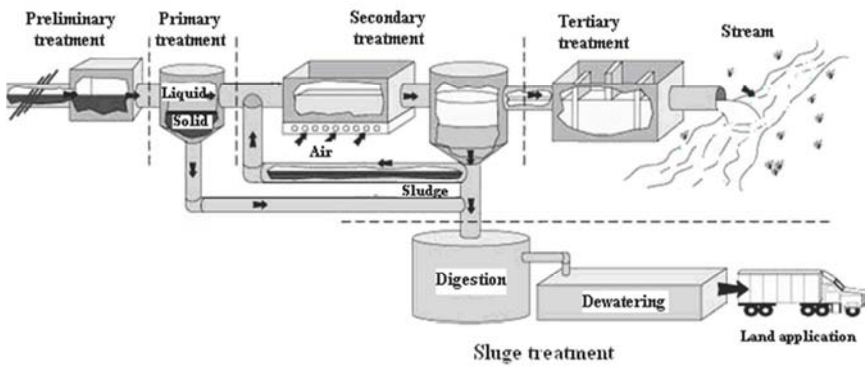


FIG.2. A typical process flow diagram of a WWTP and various treatment level.

Preliminary treatment

Primary treatment removes the materials that can be easily collected from the raw wastewater and disposed of. The typical materials that are removed during primary treatment include fats, oils, and greases, sand, gravels and grit, larger settleable solids and floating materials. This is most commonly done with a manual or automated mechanically raked bar screen. In a typical WWTP an equalization tank is installed before the primary clarifier to guarantee a uniformity of the physical and chemical properties of the effluent, which facilitates better operational control of the plant.

Primary treatment

The main aim of the primary process is to produce a liquid effluent suitable for downstream biological treatment. Many plants have a sedimentation stage where the sewage is allowed to pass slowly through large tanks, commonly called ‘primary clarifiers’ or ‘primary sedimentation tanks’. The tanks are large enough that sludge can settle and floating material such as grease and oils can rise to the surface and be skimmed off. The settled sludge is moved to the hoppers by means of a sludge scraper mechanism.

Secondary treatment

The purpose of secondary treatment is the removal of soluble and colloidal organics and suspended solids that have escaped the primary treatment. This is done through biological processes by using naturally occurring micro-organisms. It is called the activated sludge process. The secondary processes are carried out in two units: aeration tank and second clarifier. Air is blown into the wastewater in an aeration tank to provide oxygen to the ‘active biomass’, which uses the oxygen in consuming organic pollutants and nutrients in the wastewater. As the result of the process sludge (solid organic material) is created. The sludge is removed at the secondary clarifier as it settles under gravity to the bottom of the clarifier. The sludge could be disposed somewhere or is pumped to anaerobic digesters for further treatment. The clarified wastewater may be discharged to surface water systems or goes for disinfection.

Tertiary treatment

The tertiary treatments are required to obtain treated water of usable quality. In a full treatment WWTP the clarified water is processed further in tertiary treatment to reduce pathogens, which are micro-organisms that can pose a risk to human health. Chlorine is usually dosed into the treated wastewater stream for disinfection. In some cases, the UV light is employed to reduce the pathogens. The other tertiary treatment processes are filtration, lagooning, wetlands and nutrient removal processes. More than one process may be used at any treatment plant. The treated wastewater can be reused for irrigation or other purposes.

Sludge treatment

The sludge collected during the primary and secondary treatment processes contains a large amount of biodegradable materials, and must be treated to reduce the amount of organic matter and the number of disease-causing microorganisms present in the sludge. The most common treatment options include anaerobic digestion, aerobic digestion, and composting. The treated sludge is dewatered to reduce the volumes and transported to off-site for utilization or disposal.

1.3. PROCESS UNITS OF WASTEWATER TREATMENT PLANT AND POSSIBLE RADIOTRACER APPLICATIONS

1.3.1. Equalization tanks

The continuously working equalization tanks are intended to equalize chemical composition and the volumetric flow rate of wastewater. They are located upstream of biological and chemical treatment facilities. Equalization systems are used when the pH and/or flow rate are largely fluctuating. The use of these tanks protects biological processes against sudden changes in pollutants concentration which are dangerous for stability of micro-organisms in biological treatment of wastewater. Since the size of these equalization vessels are large (several thousand m^3), radiotracer offers a unique opportunity to check the performance of the equalization tank by assessing its mixing characteristics, presence of dead (stagnant) zones and short circuiting. Experimental RTD response is analyzed using mathematical models to asses the efficacy of the equalization tank.

1.3.2. Mixers

For increasing the efficiency of particle separation from wastewater, some coagulants and flocculants are added. The goal of the chemicals is to reduce the surface charge carried by small colloidal particles and reduce its zeta potential, so that these flocks, when contacted can agglomerate and grow in size, which can be easily separated by a process of sedimentation. The chemicals are mixed with effluent at the rapid (flash) mixer and the mixture goes to slow mixer where gentle agitation increases the flock collision frequency for making them grow in size to facilitate their settlement in the clarifier (Fig. 3).

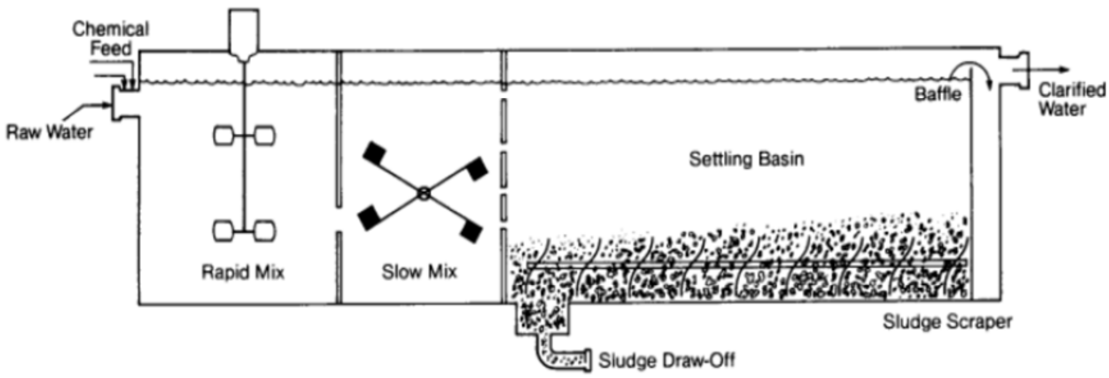
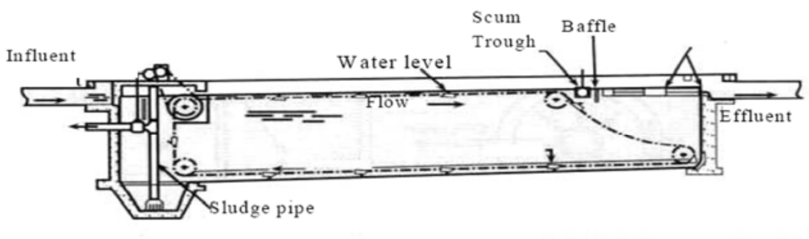


FIG.3. Mixer in rectangular clarifier.

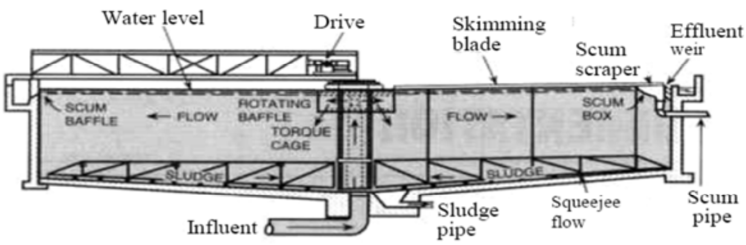
1.3.3. Primary clarifiers

A clarifier is designed to produce both a clarified effluent and a concentrated sludge. There are three main designs, namely, horizontal flow, solids contact and inclined surface clarifiers. The process of primary clarification is normally realized in circular clarifiers with diameters of 20~40 m, depth of 2~3 m. In most popular version the input is realized by axially located pipe that feed the tank. The wastewater output is normally realized by overflow on tank circumference. A low speed scraper arm at the bottom of the clarifier dislocates the sediment to the centre of clarifier where it is removed.

Most commonly used design in wastewater treatment is horizontal flow system. Horizontal flow clarifiers may be rectangular or circular in shape (Fig. 4). The flow in rectangular basins is rectilinear and parallel to the long axis of the basin, whereas in centre-feed circular basins, the water flows radially from the centre towards the outer edges.



(a) Parts of a rectangular basin



(b) Parts of circular tank

FIG.4. Settling basin with horizontal flow.

Both types of basins are designed to keep the velocity and flow distributions as uniform as possible in order to prevent eddy currents. The bottom surface slopes slightly to facilitate sludge removal. In rectangular tanks the slope is towards the inlet end, while in circular tanks the bottom is conical and slopes towards the centre of the basin.

The volume flow rate of wastewater has to be optimized for obtaining the wastewater residence time sufficient for sedimentation process realization. Liquid ***radiotracers*** are used for determination of liquid phases flow structure in a clarifier at a volume flow rate. The RTD function of liquid phases gives a possibility to calculate the mean residence times of water, evaluate the size of dead volume, and propose the appropriate flow model. Solid ***radiotracers*** are used to asses axial concentration profile (degree of settling of the solids) of the solid phase (flocks). A continuous monitoring of the radioactivity associated with the settled solids taken out from the bottom and the solids carried over through the overflow allows estimating the sedimentation efficacy of the classifier.

These radiotracer techniques are most ideal methods to evaluate the performance of various designs of clarifier under a variety of operating conditions (flow rate and solid concentrations). The turbidity level (unsettled flock concentration) expected from a well performing clarifier is around

0.25g/L, which is very difficult to measure on-line using conventional optical methods, and hence ***radiotracers*** labeled solid are ideal for this application.

1.3.4. Sand filters

Sand filters (Fig. 5) are occasionally used in the treatment of sewage as a final polishing stage. In these filters the sand traps residual suspended material and bacteria and provides a physical matrix for bacterial decomposition of nitrogenous material, including ammonia and nitrates, into nitrogen gas. After the primary clarifier the wastewater, if it is to be discharged, are directed to sand filter station, where additional process of solid particles removal take place. Passing the wastewater through a sand filter strains out the flock and the particles trapped within it reducing numbers of bacteria and removing most of the solids. The medium of the filter is sand of varying grades. Where taste and odor may be a problem, the sand filter may include a layer of activated carbon to remove such taste and odor.

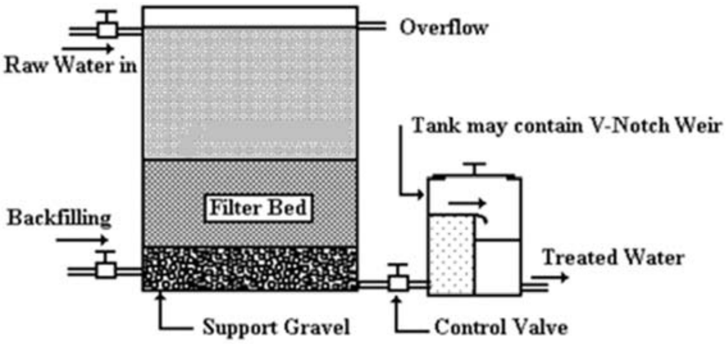


FIG.5. Fixed media sand filter.

Sand filters become clogged with flock after a period in use and they are then backwashed or pressure washed to remove the flock. The performance of the filer systems can be evaluated using radiotracers. The radiotracer RTD measurement techniques can be used for identification of the presence of unfavorable water channeling and also for estimation of the accumulated solid volume.

1.3.5. Disinfection unit

The purpose of disinfection in the treatment of wastewater is to substantially reduce the number of microorganisms in the water to be discharged back into the environment.

If the effluent after the primary treatment requires a secondary treatment, then some level of disinfection using chlorine or ozone is carried out to remove pathogenic bacteria so as to avoid their interference with subsequent biological treatment processes carried out in the secondary treatment stage.

Common methods of disinfection include ozone, chlorine, or ultraviolet light. Ozone is generated by passing oxygen through a high voltage potential. Ozone is very unstable and reactive and oxidizes most organic material, thereby destroying many pathogenic microorganisms. In many countries, ultraviolet (UV) light is becoming the most common means of disinfection because of the concerns about the impacts of chlorine in chlorinating residual organics. However, chlorination still remains as the most common form of wastewater disinfection due to its low cost and long-term history of effectiveness.

These disinfection devices are usually standard gas-liquid contacting devices such as bubble columns, packed columns, liquid jet ejectors etc., which have been well analyzed and studied in the chemical industry using radiotracer technology. The effectiveness of disinfection depends on mean residence times of phases, mixing characteristics and flow pattern in the devices. All these technological parameters can be measure using radiotracer techniques.

1.3.6. Aeration tanks

The wastewater from the primary clarifier is sent to the aeration basin for activated sludge process. The activated sludge process is a wastewater treatment method in which the organic matter of wastewater is interacted with a mixed population of microorganisms in an aquatic aerobic environment. The microbes convert carbon into cell tissue and oxidized end products that include carbon dioxide and water.

Once the wastewater has received sufficient treatment, the mixture of raw wastewater and biological mass is discharged into settling tanks for secondary sedimentation process. Part of the settled material (sludge) is returned to the head of the aeration system for further treatment (Fig. 6).

The equipment used for wastewater aeration is required for the biological process and also to provide mixing to keep solids suspended for more effective treatment. Although there are many types of aeration systems, the two basic methods of aerating wastewater are through mechanical surface aeration to entrain air into the wastewater by agitation, or by introducing air with submerged diffusers (Fig. 7)

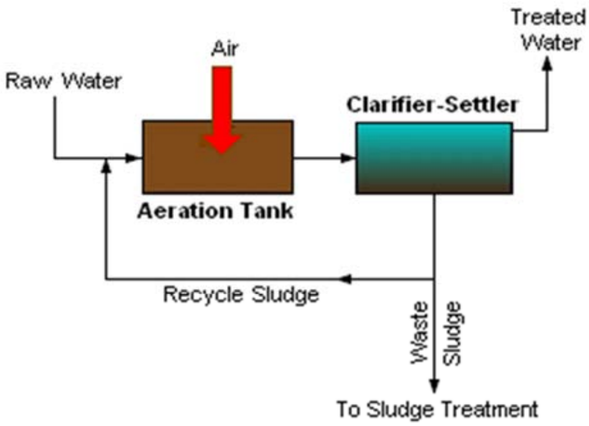


FIG.6. Principle of treatment in aeration tank.

FIG.7. Aeration systems with submerged diffusers (left) and mechanical surface aeration (right).

Aeration systems for conventional activated sludge wastewater treatment plants typically account for 45 to 60% of a treatment facility's total energy use. Therefore, efficient operation of the aeration systems is very important in economic and environmental point of view. *Radiotracers* can be used for determination of RTD functions of liquid and solid phases separately. On the base of this information the mixing processes intensity can be evaluated. By using radioisotope labeled solid particles the information concerning the sediment distribution in tank volume (zone of solid phase stagnation localization) can be obtained. The analysis of RTD functions indicates the presence or absence of short-circuit (by-pass flow) and rate of active volume of tank.

1.3.7. Biological filter

In some cases the wastewater biological treatment can be realized in vertical cylindrical biological filters in which the biologically active mass (microorganisms) is stabilized on porous bed. During the purification process the wastewater and gas (air) are flowing co currently from bottom to top of filter. On the passage through the filter, microorganisms consume the pollutants and increase the volume of the active biomass. The chemical engineering analogous of this unit is adsorption column. The effectiveness of this kind of unit depends on the regime and structure flow of all three phases present in apparatus. All the requirements for this type of liquid-solid-gas reactor have to be realized.

The ***radiotracer*** method can be utilized for determination of RTD of liquid and gas phases, identification of gas bypass, liquid short circuit and other disturbances in flow structure, simultaneously by appropriately choosing radiotracers for liquids, gases and solids.

1.3.8. Secondary clarifiers

The secondary (final) clarifier follows the aeration unit. After biological treatment in aeration tanks, the wastewater with suspended biomass is directed to secondary clarifiers for sediment removal. The sedimentation process is realized in rectangular or circular clarifiers, which are similar in construction to the primary clarifiers. In principle the physical processes occurring in secondary and primary clarifiers are the same. The sediment in secondary clarifiers is biomass which is much lighter than inorganic precipitation in primary clarifier, and it takes longer time to be settled. Therefore, the wastewater flow rate has to match with the volume of clarifier to secure the sufficient time for sludge particles sedimentation, which is normally 2-3 hours. The secondary clarifier must not only produce an effluent of acceptable quality, but must also produce sludge of sufficiently high solids concentration. The final clarifier, therefore, is a very important treatment unit. If it does not fulfill its function properly, the desired effluent quality may not be achieved.

The design of secondary clarifier is more complicate and still controversial. Bench scale studies using sewage and radioactive tracers have corroborated the higher efficiency of the peripheral-feed tank over center feed models. Center feed basins showed inefficiencies resulting from under utilization of the tank volume and short-circuiting of the incoming flow. It was found when comparing hydraulic characteristics of the peripheral-feed basin to that of the center-feed basin that short-circuiting could be reduced 3 - 4 times. Improved performance was attributed, in part, to a 7 to 9 time's reduction of inlet velocities into the clarification zone.

Figure 8 shows a peripheral-feed/peripheral-overflow secondary clarifier, which is designed for optimum performance of the activated sludge. The secondary clarifier is made up of three basic hydraulic components, the inlet channel raceway, the effluent channel and the settled sludge withdrawal header.

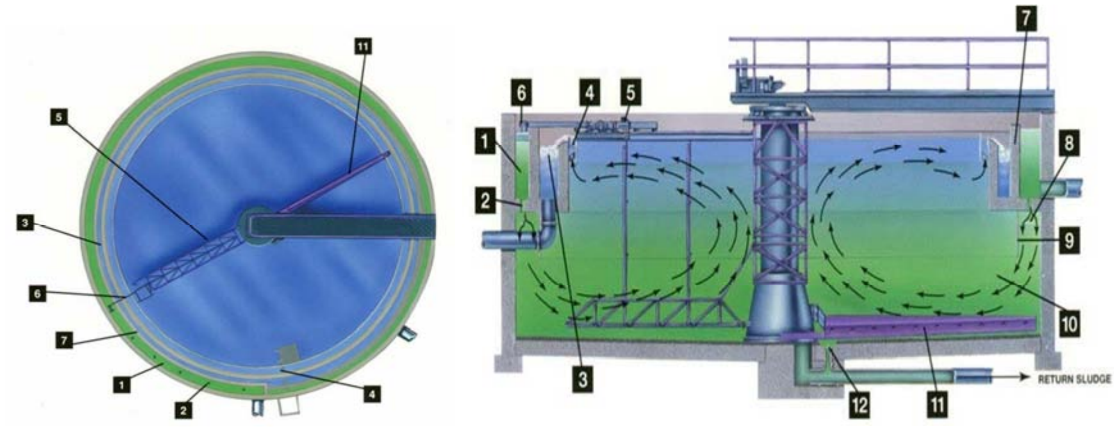


FIG.8. Secondary clarifier: peripheral-feed/peripheral-overflow model.

Where: 1. Influent channel; 2. Inlet orifice; 3. Effluent channel; 4. Weir and scum baffle; 5. Skimming - Main tank; 6. Skimming – influent; 7. Divider wall; 8. Deflector baffle; 9. Influent skirt baffle; 10.Large inlet area; 11.Sludge remover header; 12. Tank drain.

The wastewater flow structure in a secondary clarifier depends on the geometry of the clarifier, such as constructions of wastewater inlet and outlet, location of baffles and mechanical movement of scraper. Tracer techniques have been using in bench scale studies to evaluate the efficiencies of different designs. A contributing factor to the wide variance in preferred designs has been a lack of an agreed testing protocol and standardized reporting method. Radiotracer is the only tool to document performance of the clarifiers. Radiotracer can be used for the determination of liquid phase RTD function. The most important information provided by this function is the mean residence time and liquid phase flow structure, on which the efficiency of sedimentation process depends.

1.3.9. Discharge of wastewater

The wastewater after the cleaning processes are partially recycled for using them as a technological water or for other process purposes, and residue is discharged to natural water receivers like rivers, sea, lakes.

Surface water constitutes a primary receiver for sewage discharged in liquid form. In order to protect surface water against excessive contaminations it is necessary to have sufficient knowledge about spreading and dilution of pollutants in the receiver water. The radiotracers are used for investigation of interrelations between receiver water and sewages discharged there. Such investigation is particularly focused on spreading of pollutants and measurement of intensity of their mixing with natural water. The radiotracer experiments carried out on rivers and sea allows calculate the values of dispersion coefficients describing the water region, optimize the discharge point localization in receiver and evaluate the length of perfect mixing is reached. From the point of view of water pollution control it is desirable that such process terminates within possible shortest distance from a point of discharge.

1.3.10. Anaerobic biological digester

Sewage sludge is produced from the treatment of wastewater and consists of two basic forms - raw primary sludge (basically faecal material) and activated secondary sludge. Sludge collected during the primary and secondary treatment processes contains a large amount of biodegradable material making it amenable to treatment by a different set of micro-organisms, called anaerobic bacteria, which do not need oxygen for growth. This takes place in special fully enclosed anaerobic digesters heated to 35^0 C (Fig. 9).

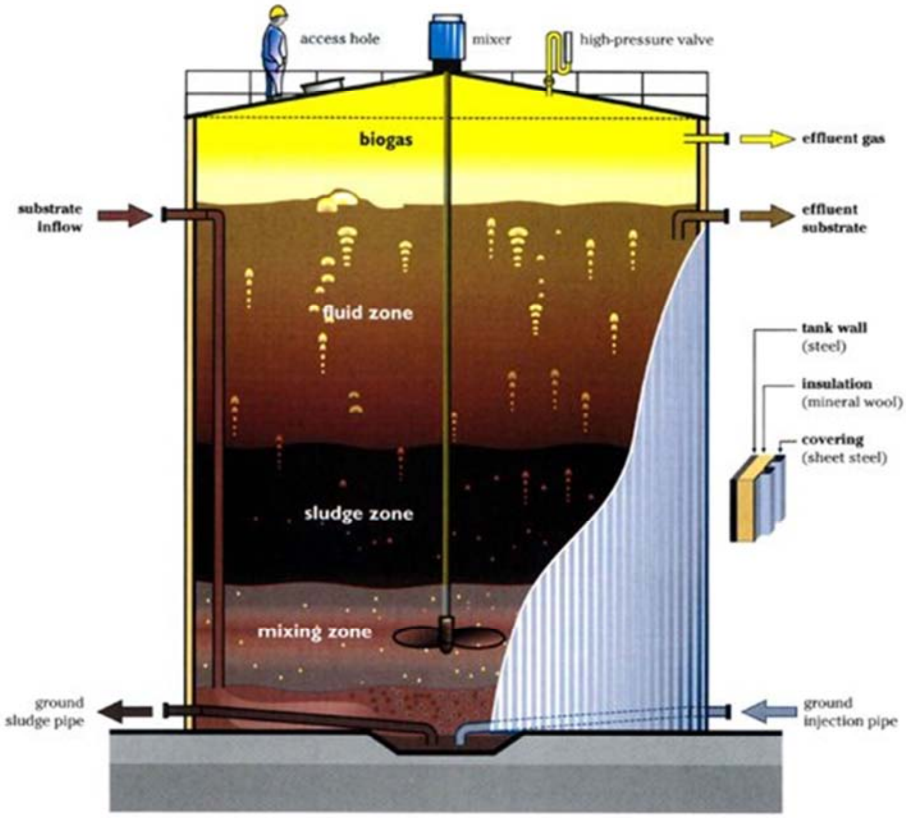


FIG.9. Reactor configurations for anaerobic process.

The digestion process is continuous. Fresh feed sludge must be added continuously or at frequent intervals. Digestion results in a 90% reduction of pathogens and the production of a wet soil-like material called ‘biosolids‘ that contain 95-97% water.

The advantage of the anaerobic process is such that it does not consume any energy for oxygen transfer but in fact converts the organic pollutants to combustible gases such as methane and hydrogen along with the generation of the carbon dioxide as a result of metabolic activity of the anaerobic microbe. However, the disadvantage of the anaerobic process is that it is considerably slower than the aerobic digestion process. Anaerobic process usually takes 15-30 days as against 12 to 24 hours needed for the aerobic treatment to achieve equivalent quality of the treated effluent. Because of the long residence times required, the volume of these digesters is very large (in the range of 5000 to 20000 m^3).

A variety of anaerobic digester designs are currently used, where agitation is provided, either by mechanical agitation or by the sparging of the same gas to keep the microbes in suspension for their homogeneous activity.

In addition to chemical composition of sludge and condition of the microorganisms, dynamic characteristic of the sludge is a major factor on the operation efficiency of a digester. As the digester is 3-phase system of large dimensions, radiotracer is the most suitable tool for the investigation of the system. Various radiotracers can be used to get information of the gas, solid and liquid phase fractional hold-ups, their spatial distribution, their movement and the mean residence times.

1.3.11. Natural treatment systems (Lagoons)

Wastewater treatment plants are complex and costly. There is a possibility to utilize so called ‘natural systems’ for wastewater treatment, which take advantage of physical, chemical, and biological processes that occur in natural environment when water, soil, plants, micro-organisms and the atmosphere interact. Natural treatment systems include lagoons (Fig. 10), floating aquatic plants and constructed wetlands. All natural treatment systems are preceded by some form of mechanical pretreatment for the removal of gross solids. Where sufficient land suitable for the purpose is available, these systems can often be the most cost-effective option in terms of both construction and operation. They are frequently well suited for small communities and rural areas.

FIG.10. Aerated lagoon system.

Lagoons are pond-like bodies of water or basins designed to receive, hold, and treat wastewater for a predetermined period of time. In the lagoon, wastewater is treated through a combination of physical, biological, and chemical processes. Much of the treatment occurs naturally, but some systems use aeration devices to add oxygen to the wastewater. Aeration makes treatment more efficient, so that less land area is necessary. Aerators can be used to allow existing systems to treat more wastewater. Wastewater usually must remain in aerobic lagoons from 3 to 50 days to receive adequate treatment. Exact detention times for wastewater in lagoons are based on factors such as the particular design, the amount of wastewater to be treated, and the level of treatment desired.

All radiotracer techniques adapted for surface water transport are equally applicable to assess the efficiency of the hydraulic transport through the system and its treatment capability. Mean residence time and the size of effective volume as well as the location of stagnant zone can be measures using radiotracer techniques.

2. TRACER TECHNIQUES AND THEIR UTILIZATION IN WASTEWATER TREATMENT PLANTS

2.1. PRINCIPLE OF TRACER METHOD FOR RESIDENCE TIME MEASUREMENT

A tracer is any substance whose physical, chemical, or biological properties provide for the identification, observation and study of the behavior of various physical, chemical or biological processes (dispersion or concentration, flow, kinetics and dynamics, chemical reactions, physiological interactions etc.), which occur either instantaneously or in a given lapse of time.

Operation of a wastewater treatment plant (WWTP) or lagoon can be deceptively complex. Given unsatisfactory state of current theoretical approaches, there is a need to be able to assess performance practically. Tracer techniques are highly useful tools to investigate the efficiency of purification in wastewater treatment installations aiding both their design and performance optimization. There are many kinds of tracers. The radioactive tracers are the most sensitive and are largely used for online diagnosis of various operations in WWTP. The success of radiotracer applications rests upon: (1) the extremely high detection sensitivity of radiotracers facilitates their use in large scale WWTP treating millions of liters of effluent, (2) the strong resistance against severe process conditions; (3) the on-line investigation mode without sampling; (4) the multi-tracer simultaneous tests for solid and liquid phases.

The tracing principle consists in a common impulse-response method: injection of a tracer at the inlet of a system and recording the concentration-time curve, C(t), at the outlet (Fig. 11). A sharp pulse of tracer is injected upstream of the vessel and a detector located at the inlet marks time-zero. A second detector located at the outlet records the passage of the tracer from the vessel. The response of this detector is the residence time distribution (RTD). This methodology is applicable with any type of tracer and any type of detection system, even manual sampling.

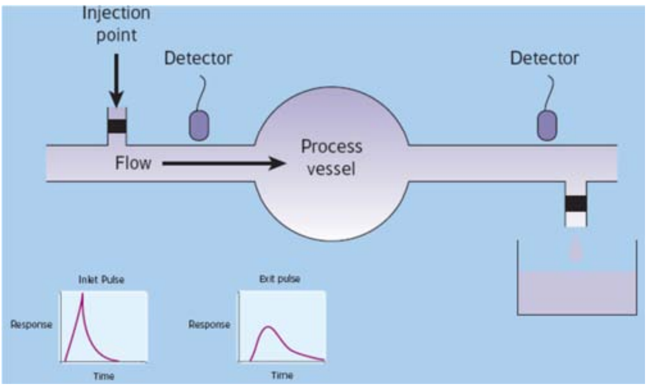


FIG.11. Principle of tracer residence time distribution (RTD).

Basic radiotracer methodology includes the measurement of the RTD and its utilization for troubleshooting and diagnosis. The normalized RTD function E(t), is represented by the equation:

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

where C(t) is the tracer concentration at the outlet of the system at time ‘t’.

The instantaneous (Dirac pulse) tracer injection is normally applied in practice, because it gives directly the RTD, requires less tracer, is simple and rich in information. An injection is considered as instantaneous when its duration is less than 3% of the mean residence time (MRT) within the system.

The RTD and MRT are parameters that are extremely pertinent to the operation of chemical reactors, influencing both the throughput and the quality of the product.

The concept of the RTD is fundamental to any engineering reactor design. The real time experimental RTD tracing is simple and reliable; it provides various important hydrodynamic parameters. From a well-conducted tracer experiment, it is expected to obtain the RTD of the traced material in a system. Accurate experimental RTD curve is crucial for system analysis or modeling.

2.2. RESIDENCE TIME DISTRIBUTION DATA TREATMENT

The analysis of the residence time distribution (RTD) data depends upon the specific aim for which the radiotracer experiment has been carried out. The simples RTD data treatment is the calculation of moments. Moments are used to characterize the RTD functions in terms of statistical parameters such as MRT and variation (σ^2). The moments are defined as:

$$M_i = \int_0^\infty t^i E(t)dt$$

where, i = 0, 1, 2, 3, ...

MRT is equal to the first moment:

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

The spread of the RTD curve is characterized by the variance (σ2):

$$\sigma^2 = M_2 - M_1^2 = \int_0^\infty (t - \bar{t})^2 E(t)dt$$

where $M_2 = \int_0^\infty t^2 E(t)dt$ is the second moment.

If N reactors are connected in series then MRT and variance of the cascade can be obtained from the following relations:

$$\bar{t}_{cascade} = \bar{t}_1 + \bar{t}_2 + \bar{t}_3 + ... + \bar{t}_N$$

$$\sigma^2_{cascade} = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + ... + \sigma_N^2$$

For a fluid flowing in a system of volume V with constant flow rate Q, the theoretical MRT (τ) of the fluid is defined as:

$$\tau = V/Q$$

2.3. RESIDENCE TIME DISTRIBUTION MODELING

Modeling a flow from RTD experimental data means to represent the experimental curve by a known theoretical function. Flow model is the quantitative description of hydrodynamic characteristics of the transported material. The model helps to understanding of a process and its prediction (simulation) for different conditions. Modeling of experimental RTD curve with theoretical functions of different flow patterns is performed using different software. The arrangements of basic flow elements are used to provide a proper model that gives a response identical or close to the signal from the tracer experiment in the system under study. This approach is sometimes known as systemic analysis.

2.3.1. Models for ideal flow: plug flow and perfect mixer

Plug flow and perfect mixer can be seen as two extreme cases, where mixing is either non existent or complete instantaneously.

In *plug flow*, it is assumed that matter flows without any dispersion. In other words this flow is pure convection. A Dirac injection is therefore transported without any deformation and shifted by a time-lag τ, which is the only parameter of the model. Mathematical expression of the RTD function for the plug flow model is:

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

where δ is the Dirac impulse function.

In case of a *perfect mixer*, tracer is assumed to be mixed instantaneously and uniformly in the whole volume of system. This model has one parameter, time constant τ which is equal to the ratio of system volume V and volumetric flow rate Q. The mathematical expression of the RTD function for the perfect mixer model is:

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

2.3.2. Basic models for non-ideal flows

Real flows normally behave as intermediates between pure convection (plug flow) and pure mixing (perfect mixer). Among these flows, many can be seen as the superposition of a pure transport (convective) effect and a dispersive effect that blurs out the concentration gradients.

Two types of basic models are axial dispersion model and perfect mixers in series model (also called ‘tanks in series’ or ‘perfect mixing cells in series’ model).

(a) Axial dispersion model

The axial dispersion (or axially dispersed plug flow) model is widely used in practice. This flow is the superimposition of convection (bulk movement of the fluid as a plug) and some amount of dispersion. The RTD function:

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

When the above equation is expressed in non-dimensional form, two parameters appear:

- A characteristic time constant $\tau = L/U$, where L is the length of the system and U is the velocity of the flow,
- Péclet number $P_e = (U.L)/D$, that represents the ratio of the convective to dispersive effects. In other words, dispersion is predominant when *Pe* is low and negligible when it is large.

The effect of varying the P_e is illustrated below (Fig. 12). The curves get sharper and sharper when P_e is increased. They always have one single peak and the peak height and tail length are correlated (tail is short when peak is sharp and vice versa).

(b) Perfect mixers in series model

As indicated by its name, the 'perfect mixers in series' model is composed of J perfect mixing cells connected in series. Some mathematical manipulation leads to the RTD function in time domain:

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

where J is the number of mixing cells in series.

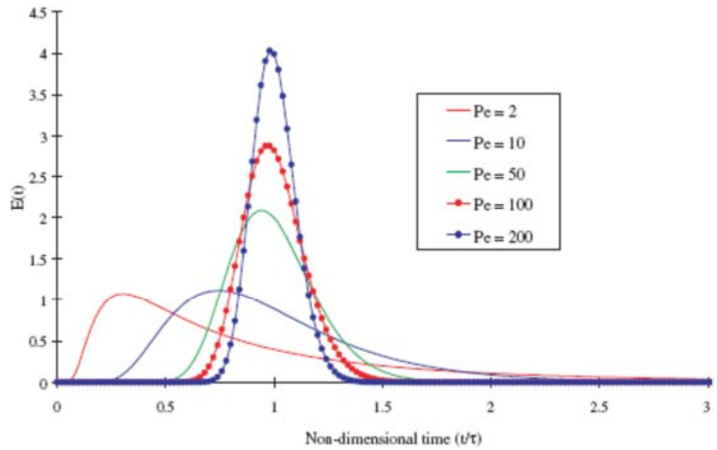


FIG.12. Axially dispersed flow model as a function of the Péclet number (Pe).

This expression behaves in much the same way as the one for the axially dispersed plug flow model, J playing the same role as *Pe*. As J gets large, impulse response gets closer and closer to the axial dispersion flow model. The following relationship is often quoted for large values of J:

$$J \approx P_e/2 + 1$$

The effect of varying J is shown in the Fig. 13.

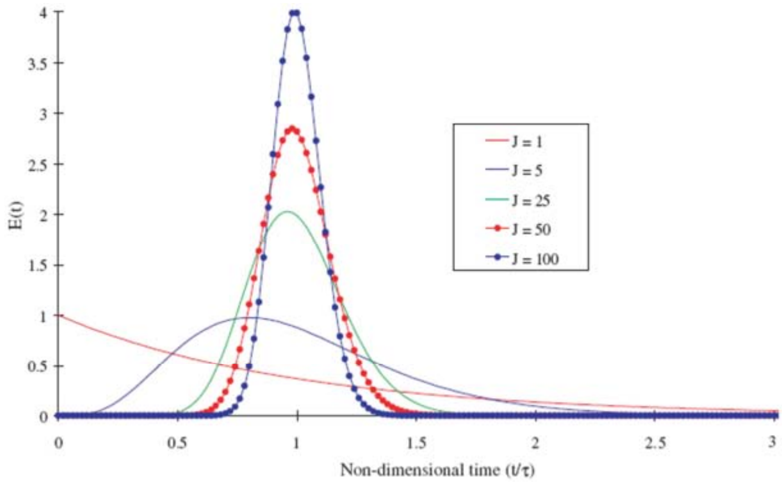


FIG.13. Perfect mixers in series model as a function of J, number of perfect mixers.

One last question is the choice between the axially dispersed plug flow model and the mixer in series model, since both can be used to represent experimental curves with one peak and 'moderate' tailing. This question holds only for low to medium values of J or P_e. On the one hand the axially dispersed plug flow model can be thought better in a continuous system, like a pipe or a column. On the other hand the physical relevance of this model can be held to suspicion at low Peclet numbers. Experience has proved that the easiest to manipulate model is the perfect mixers in series, thus general recommendation is to try this model for simulation the experimental data at the beginning.

(c) Dispersion and exchange models

The perfect mixers in series with exchange model is often used in RTD applications. The conceptual representation of this model is given in Fig. 14.

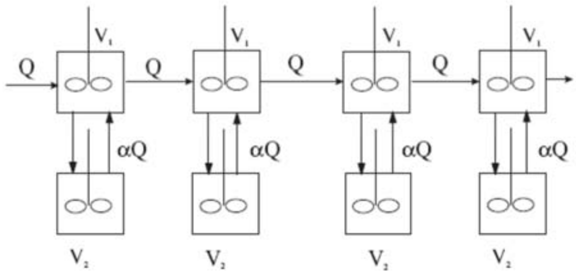


FIG.14. Perfect mixers in series with exchange.

Main flow rate *Q* goes through a series of J perfect mixers in series of volume V_1; each perfect mixer exchanges flow rate αQ with another mixer of volume V_2. This model has four independent parameters that can be combined in many ways; one way is to consider parameters:

$$\tau = \frac{JV_1}{Q},\ t_m = \frac{V_2}{\alpha Q},\ k = V_2/V_1 \text{ and } J.$$

τ is the mean residence time for the main flow; t_m is the time constant for the exchange between main flow and stagnant zone, or the inverse of a 'transfer coefficient' between these two perfect mixing cells (the larger t_m, the smaller the exchange), k represents the relative volume of the stagnant zone with respect to the whole volume. This model has practical value in cases where a stagnant zone exists. An example of a tracer test in a wastewater treatment unit is shown in Fig. 15.

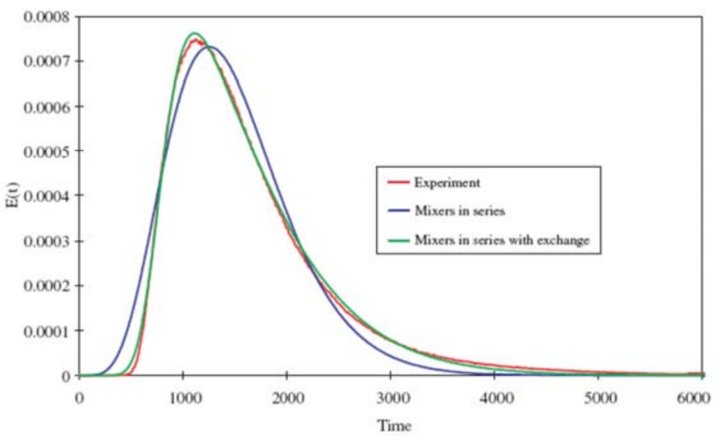
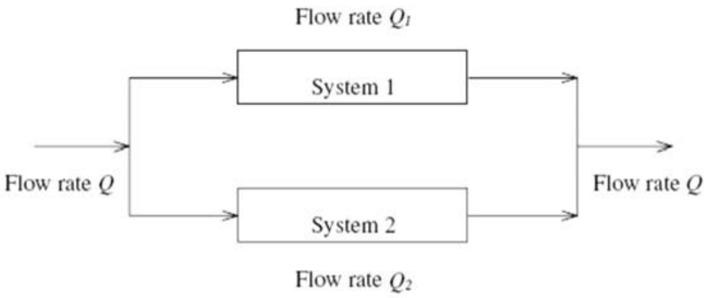


FIG.15. Comparison of mixers in series and mixers in series with exchange model.

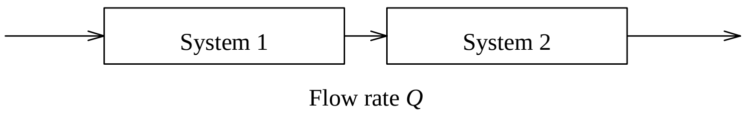
The experimental data has been attempted successively to fit with the mixers in series and the mixers in series with exchange models. As seen the model of mixers in series with exchange fits better and practically it has better sense from the water flow dynamics point of view. This model is suitable for a number of processes (river flows, flow of chemically active substances in porous media, etc.).

2.3.3. Combination of basic models

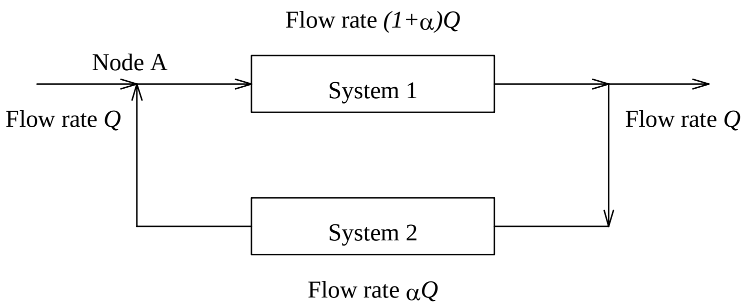
The models reviewed above are obviously not able to represent all possible tracer experiments. It is therefore necessary to have a set of rules for combining these models, in order to accommodate any shape of RTD or impulse response function. Basically, models can be associated in three ways: parallel, series and with recycling (Fig. 16 a, b, c).



(a) Parallel combination



(b) Combination in series



(c) Models with recycling (part of flow rate (αQ) is recirculating)

FIG.16. Combination of basic models.

2.3.4. Optimization procedure - Curve fitting method

Residence time distribution (RTD) model is a time function with some parameters. Modeling means to match the RTD model to the experimental RTD curve. The evaluation of the model parameters is performed by means of the optimization (curve fitting) of the experimental RTD $E_{exp}(t)$ with the model (or theoretical RTD) $E_m(t,p_i)$, where p_i are the model parameters (which represent the process parameters).

Fitting the model RTD function with the experimental RTD curve is performed by the least square curve fitting method.

The quality of the fit is judged by choosing the model parameters to minimize the sum of the squares of the differences between the experimental data and model.

$$\varepsilon = \int_0^\infty \left[E_{exp.}(t) - E_m(t, pi)\right]^2 dt \Rightarrow \textbf{Minimum}$$

The values of the model parameters corresponding to the minimum value of the squares of the differences are chosen as the best.

There are various commercial and homemade RTD software packages for modeling experimental RTD curve.

The experience has shown that:

- tracer work is first of all an experimental one and all of efforts should be dedicated to the quality and reliability of the measurements,
- experimental data may be interpreted at different level by tracer specialist or in collaboration with chemical engineering specialist in complex cases ,
- tracer experimental data remain of prime importance and the results of the experiments are not linked to the output of particular software, but different software facilitates extraction of information and interpretation, in particular for complex process analysis.

2.4. RESIDENCE TIME DISTRIBUTION FOR TROUBLESHOOTING

RTD and MRT are two important parameters of continuously operating industrial process systems. They are analyzed either to identify the cause of malfunctioning or to characterize the degree of mixing in the system. There are a number of reasons for imperfect mixing, i.e. presence of dead (or stagnant) volume, occurrence of channelling, split in parallel or preferential flows, bypass or short circuit exit flows and holding-up. These symptoms are reflected in the experimental response curves.

Experience has shown that two common phenomena may happening in any kind of reactors are short circuiting stream and dead volume (Fig. 17). A short circuiting stream is characterized with a short residence time within the tank. Dead volumes are stagnant or scaled zones that are not active in the process. Dead zones reduce the effective (active) volume, as a consequence, the process efficiency is lower that expected.

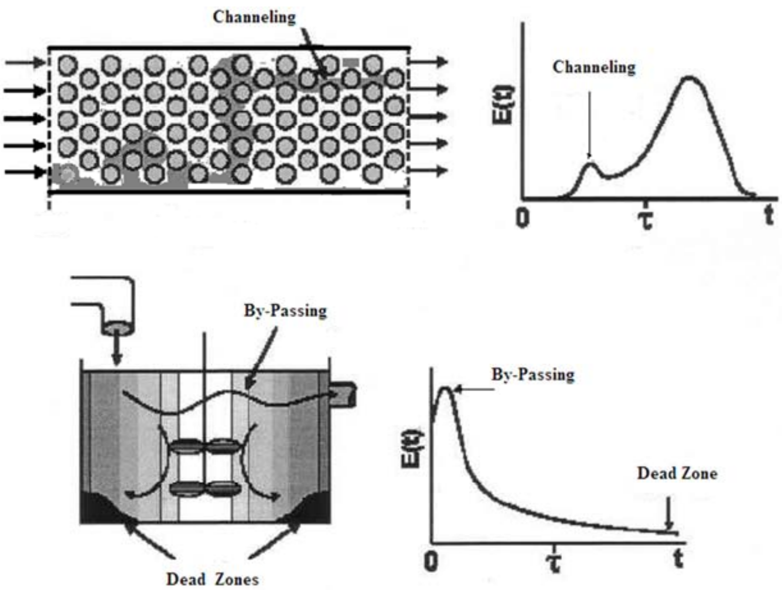


FIG.17. Illustrations of a porous media with channeling, and of a tank reactor with short circuiting stream (bypass) and with dead zone.

The experimental RTD curve gives many indications for troubleshooting inspection of engineering reactors or flow systems. Most of the malfunctions could be identified and quantified. The analysis of a process unit for the purposes of determining dead space or channeling need not require sophisticated mathematical treatment of the data because the aim is not to develop a model, but simply to determine whether or not the equipment is functioning properly.

2.4.1. Dead and stagnant volume

Looking more closely at a continuously stirred tank, it is possible to determine what fraction of the tank is 'active'.

The theoretical MRT, τ, of fluid entering a processing vessel (or reactor) is given by the equation $\tau = V/Q$, where V is the vessel volume (as designed) and Q is the volumetric flow rate (as measured during the tracer test). However, the real MRT can be experimentally determined from the measured RTD curve. Comparing theoretical MRT with real (or experimental) MRT provides for dead or stagnant volume inside the vessel.

For a stirred tank in which a fraction of the total volume is occupied by a stagnant zone the experimental RTD curve will not behave the same way as for a perfect mixer tank; it will exhibit a long tail that indicates the slow exchange of flow between the active and stagnant volume.

The dead volume is normally considered as blocked zone where the traced fluid does not penetrate because of scaling, solidified material or other barrier. To estimate the amount of the dead volume present in the system firstly the active (or real) mean residence time has to be calculated:

$$\tau_a = V_a/Q$$

where V_a is the active volume:

$$V_a = V - V_d$$

and V_d is the dead space or volume.

Thus,

$$\tau_a = V_a/Q = (V - V_d)/Q = \tau - V_d/Q$$

and:

$$V_d = Q(\tau - \tau_a)$$

Now the fraction of the tank volume that is dead, f_d, can be calculate using the following expression:

$$f_d = V_d/V = Q.(\tau - \tau_a)/(Q\tau) = 1 - \tau_a/\tau$$

RTD analysis of a stirred tank system (or any other system) not only allows for the determination of whether or not there is dead space in the system, but also gives a quantitative estimate of its size. It is obvious, however, that to be quantitative an accurate estimate of the true (theoretical or physical) mean residence time is necessary; this means the tank volume and volumetric flow rate must be known well. Normally $\tau > \tau_a$, but if not, there are several possible reasons (i) error in flow rate measurement (ii) error in volume measurement (iii) the tracer is absorbed and held back in the system.

2.4.2. Bypassing and channelling

Bypassing is another commonly occurring malfunction in wastewater process units. It is especially serious in two phase flows. If the experimental RTD curve shows two peaks, the first one reflects channeling of the tracer (flow) directly from the input to the output, while the second peak represents the main flow of the fluid inside the system. The ratio of the first peak area to the sum of the two peak areas gives the percentage of the channeling effect (or bypass transport).

The amount of bypassing could be easily estimated when the experimental RTD curve has two distinct peaks; ratio of peak areas provides the ratio of bypassing. However, in some cases the experimental RTD curve may not show two distinct peaks due to exchange between bypassed and the main part of the fluid. In such cases, the cumulative RTD curve (F curve) could be useful for bypass detection. The initial rapidly increasing part of the cumulative F curve gives fraction of the bypassed fluid.

Experimental RTD curve might show two or more peaks depending on the fluid transport and process characteristics. These peaks might represent parallel or preferential flows. Bypassing is considered only when comes first and fast (less than 10-15% of the MRT) and when its area consists of less than 10-15% of the main flow curve; while the amplitude of the bypassing peak might be higher or lower than the main flow peak.

2.5. INTEGRATION OF RESIDENCE TIME DISTRIBUTION TRACING WITH COMPUTER FLUID DYNAMICS SIMULATION

The concept of residence time distribution (RTD) is fundamental to any reactor design. The RTD for a process equipment is measured using tracer methods to detect undesign flows such as bypass, channeling and dead zones. The experimental RTD data provides various important hydrodynamic informations, but it is impossible to localize and visualize flow pattern inside the systems. The RTD method still remains a global approach. RTD systemic analysis requires the choice of a model, which is often semi-empirical and rather idealized.

Recently, profiting from the progress in computer processing, the computer fluid dynamics (CFD) simulation became capable of predicting the complete velocity distribution in a vessel. The CFD provides detailed spatial pictures of the insight of a process, such as flow patterns and velocity map. CFD can be easily coupled to modern tools for three-dimensional visualization, creating maps of velocity vectors, streamlines, etc. However, due to lack of physical experimental data the CFD calculation provides qualitative results only, especially in systems with strong interaction of hydrodynamics with physico-chemical reactions. This is the reason why CFD models have to be verified and validated by experimental tracer RTD results.

In fact, these two approaches, experimental and numerical, are complementary to each other. The CFD can be used also to complement the information obtained from the RTD systemic approach. The CFD provides data that can quantify RTD systemic model, which means the CFD model, can ‘degenerate’ into more quantitative RTD systemic analysis, providing more comprehensive results for chemical engineers. The RTD systemic approach detects and characterizes main features of the flow while CFD enables to locate them. The trend is to combine experimental RTD and numerical CFD approaches to obtain reliable quantitative results for processing units.

A simple case illustrating CFD-RTD interaction is described. On the experimental side, a 1.4 liter stirred tank has been investigated to measure the RTD as a function of flow rate using a chemical tracer. The experimental RTD curve showed a perfect mixer. The CFD FLUENT predictions were found to be in excellent agreement with the RTD experiment (Fig. 18). With the aid of CFD simulations, process investigation over a broad range of flow rates and impeller RPM values can be facilitated without further need for tracer experimental work.

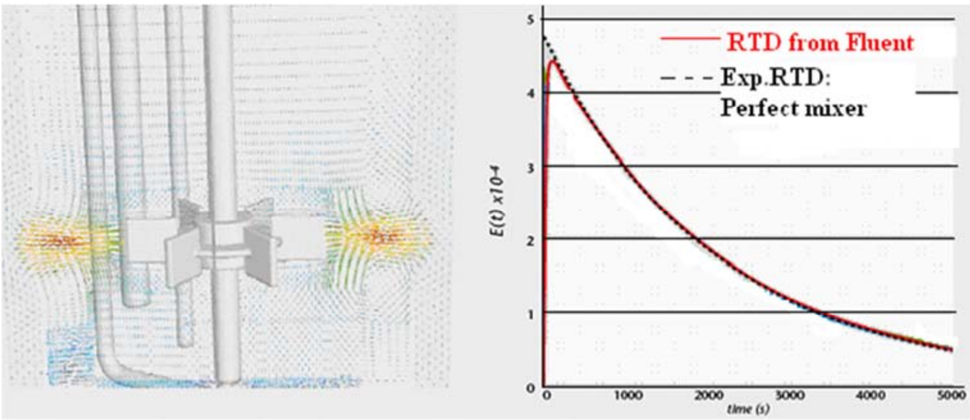


FIG.18. Experimental and CFD calculated RTD curves for fluid flow in a 1.4 liter stirred tank.

The performance of wastewater treatment processes depends on chemical/biological treatment efficiency and hydraulics. The CFD method is used in investigation of WWTP to predict:

- the exact flow rate discharged by combined sewer overflows going to a river or sea without treatment,
- the sludge concentration distribution and the sludge blanket in secondary settlers,
- the mixing efficiency and the recirculation velocity induced by immersed impellers in an activated sludge basin,
- the impeller pumping efficiency for various sludge types,
- the fluence distribution in a UV reactor by coupling the hydrodynamics with the radiation field.

All of the WWTP processes simulated using CFD have been validated against tracer RTD tests. Once validated, CFD becomes an effective tool for improving the understanding of many processes, and for exploring several scenarios. It can be used for process design and the optimization of process performance. Different operating conditions and/or different geometrical dimensions can be tested at a lower cost and in less time than with the experimental approach.

Troubleshooting can also be more effective with the use of the validated CFD model, because it can help engineers to understand and diagnose problems quickly while, at the same time, being able to propose improvements. In addition, scale-up problems can be solved by eliminating empirical design methods. Local modifications at the smaller scale can be coupled with checking the effect at the industrial process scale

2.6. ECONOMIC BENEFITS OF TRACERS UTILIZATION IN WASTEWATER TREATMENT PLANT

Tracing technology allows movement of water mass, sludge and contaminants (whether dissolved or particulate) to be measured in a range of wastewater applications. Wastewater tracer studies are an effective tool that can be used to complement other techniques for:

- Location and quantification of sewerage network infiltration.
- Sediment dynamics studies in sewerage networks.
- Drain tagging and sewer misconnection studies.
- Particulate retention efficiency of storm tanks.
- Process fluid, grit and sludge-dynamic studies for optimization of WWTP.
- Detection of poor operating procedures and poor plant design for optimization and rehabilitation programmes.
- Wastewater treatment works flow balancing.
- Determination of effective volume in anaerobic digesters.
- Industrial effluent dispersal and impact assessments on receiving waters.

- Deposition of particulates from wastewater treatment discharges.
- Environmental impacts of outfalls.
- Validation and/or provision of empirical data for CFD models.

It is difficult to assess quantitatively the economic benefit of the use of radiotracers in WWTP unlike in industrial process systems where the value added products are manufactured. However, its economic benefit is indirectly quantified through reduced environmental impact of waste discharge. As water becomes a limiting commodity for industrial usage, the running of WWTP efficiently and optimally will become crucial and radiotracers can help in achieving the same.

In the countries where water usage and treatment contributes significantly to the final cost of manufacturing, it is imperative for the chemical manufacturers to treat WWTP as rigorously as any chemical manufacturing activities to reduce or eliminate the financial penalties that they have to pay for improper operations of WWTP.

The situation is somewhat different in respect of applications in which radioisotope technology is used to help optimize an existing process or to optimize the design of a new one. While a trouble-shooting project results in a 'one-off' economic benefit, often realized as savings, an optimization exercise results in a permanent and ongoing increase in productivity and/or product quality, leading in turn to a continuing increase in profit. Thus, the cost/benefit ratio from WWTP is likely to be considerably greater in the years to come.

Use of tracers has proved to be a cost-effective monitoring technique, providing an insight into many areas of water quality, sludge behavior, plant process and outfall dispersal. Results have enabled clients to identify areas where substantial savings in both capital and operational expenditure can be made. Economic benefit is indirectly quantified through reduced environmental impact of waste discharge. The benefits of applying tracer investigations in WWTP are operating existing WWTP plants more effectively and providing data for the design of future plants.

2.7. CONVENTIONAL TRACERS FOR WASTEWATER TREATMENT PLANT INVESTIGATIONS

The major non-radioactive tracers used for investigation of WWTP's units are chemical and optical tracers.

Chemical tracer is any easily detectable substance measurable at very low concentrations by instrumental analytical techniques such as gas chromatography, high-performance liquid chromatography, inductively coupled plasma spectroscopy, neutron activation analysis, etc. Their analysis is made by chemical methods generally off line (by sampling).

Sulphur hexafluoride (SF_6) measured by gas chromatography is an example of a chemical tracer used in air pollution studies. Reactive gases such as chlorine, sulfur dioxide and nitrogen oxides are also used for gas phase tracing. They are monitored by means of reacting them in suitable reactive solvents by bubbling the whole or a side stream of the gas flow, and the reacted liquids are either gravimetrically or photometrically analyzed. Sodium dichromate, sodium iodide, sodium chloride, sodium nitrite, lithium chloride, potassium chloride and manganese sulphate, are actively used for water tracing in hydrology. These chemical tracers are generally not suitable and convenient to be used in wastewater treatment units. However, chemical tracer studies using lithium chloride (LiCl) solution to trace water phase in different WWTP units were reported.

The LiCl tracer has following advantages:

- It is does not react or degrade in wastewater,
- It has a low detection and measurement limit (atomic absorption spectrometry),
- It has no toxicity,
- It has a very low natural concentration in urban wastewater.

Optical tracers can be divided in two categories, color tracers and fluorescent tracer. The color tracer detected parameter is the color of tracer which is measured through a light or laser beam. Wavelength has to be adapted to fluid in order not to be absorbed in it. The fluorescent tracer is excited by a light or laser beam, mainly operating in the ultraviolet (UV) region. Characteristic fluorescent radiation with a higher wavelength is emitted by the tracer and detected with a photodiode detector. These tracers are organic substances, for example, uranine, rhodamine B, sulforhodamine B, sulforhodamine G, rhodamine WT, eosine. These tracers are very difficult to be used in wastewater applications because they require transparent walls and transparent fluid. However, fluorescent tracer studies using Rhodamine WT and a fluorometer are reported for on-line investigation of water phase dynamics in some WWTP units. The fluorometer could detect as low as 0.01 µg/L of Rhodamine WT in potable water, and 0.1µg/L in industrial and sanitary sewage.

2.8. LIMITATIONS OF CONVENTIONAL TRACERS IN WASTEWATER TREATMENT PLANT INVESTIGATIONS

Gas flow rates in wastewater treatment process are very large, and there is always a problem of getting a statistically representative sample as it is practically impossible to bubble the entire quantity of the gas phase through this sampling device. Most of the conventional liquid phase tracers can not be used for tracing of wastewater. As the wastewater itself is normally heavily colored and hence the dye tracer used to color it needs to be in huge quantity which itself adds an additional load of pollutant in the effluent. These dyes are also photosensitive and hence can reduce in its intensity when exposed to sunlight for extended periods as is the case in the long treatment times used in some wastewater treatment units.

Similarly, the effluent contains a large concentrations of many inorganic dissolved solids making it highly conductive, and hence to bring about a measurable change in the conductivity in the effluent again a large quantity of electrolytes are required; this adds to the whole load of the total dissolved solids which are most difficult to remove. The addition of these electrolytes also reduces the saturation solubility of the oxygen rendering the subsequent aerobic digestion processes ineffective. The additional electrolytes also reduce the efficacy of the inorganic coagulants and flocculants due to the introduction of the additional charged particles (ions in this case).

In case of effluent treatment units such as clarifiers where the liquid phase flow velocities are very low, these electrolytic solutions are known to get stratified (form separate layer) due to their significant density differences from the effluent stream. The efficiency of the biological treatment essentially depends on the specificity of the various enzymes synthesized by various microbes in course of their metabolic activity. The enzyme specificity is critically dependent on the effluent pH (especially in anaerobic digestion) and hence addition of acid or alkali as a tracer can severely impede the biological treatment processes.

As for solid phase analysis, the standard procedure is to collect the solid samples, dry them and weigh them to measure the solid phase concentration or measure the turbidity associated with the liquid flow to account for the solid phase concentration. In the case of wastewater treatment, both these options are not practical as the wastewater contain a variety of solids differing widely in density and concentration (inorganic solid precipitates, organic biomass) and hence collecting a statistically representative sample is difficult if not impossible which will truly represent the different solids accurately.

3. RADIOTRACER TECHNIQUES

The radiotracer methodology is basically the same as described above for tracers in general. The main particularity of radiotracers is their gamma radiation emission. They offer possibility of on-line and in-situ measurements, providing information in the shortest possible time. They have high detection sensitivity for extremely small concentrations, for instance, some radionuclides may be detected in quantities as small as 10^{17} grams. The amounts of tracer used are virtually insignificant. For example, 1 Ci (37 GBq) 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 and do not introduce additional pollution load unlike conventional tracers.

Because the characteristics of the radiations differ from one radioisotope to another, several tracers may be employed simultaneously and they can be measured accurately with the help of spectrometry. For example, different phases such as solid, liquid and gases can be analyzed simultaneously by selecting proper radiotracers.

The emission of radiation is a specific property of the radionuclide, and not affected by interference from other materials in the system. Radiotracers when chosen properly are completely inert to the microbes present in the digesters and do not interfere with the biological processes. Thanks to these advantages, radiotracers can offer a complete solution to many problems, and ideal for assessing proper functioning, optimization and design of various operations in WWTP. In certain applications, such as solid transportation studies in clarifiers and anaerobic digesters, radiotracers are the only option. Table 1 gives a summary of advantages and disadvantages of conventional and radioactive tracers for their applications in WWTP.

TABLE 1. COMPARISON OF CONVENTIONAL AND RADIOACTIVE TRACER TECHNIQUES AS APPLIED TO WWTP

Table 1a. Gas tracers- *Field of applications: Aeration tank, Biological filter, Disinfection unit, Anaerobic digester.*

	Conventional tracers	Radioactive tracers
Tracers used	Cl_2, SO_2, NO_2, SF_6, etc.	^{41}Ar, ^{79}Kr, $CH_3{}^{82}Br$
Advantage	Easy availability Simple analysis	High selectivity Low detection limit In-situ/On-line measurement (no sampling)
Disadvantage	Poor selectivity Poor detection threshold Difficult to get statistically representative sample	Poor availability High costs Strict radiation safety regulations

Table 1b. Liquid tracers.- *Field of applications: Central collection network, Equalization tank, Flash mixer, Clarifier, Aeration vessel, Anaerobic digester, Dispersion of discharge in water*

	Conventional tracers	Radioactive tracers
Tracers used	Electrolytes (NaCl solution): conductivity Dyes (Rhodamine, Fluorescence): color Acids & Alkali: pH	$K^{82}Br$, $NH_3{}^{82}Br$, $^{99m}Tc_2O_4{}^-$, ^{113m} In-EDTA, ^{46}Sc-EDTA, $Na^{131}I^-$, $^{24}Na_2CO_3$, etc.
Advantage	Easy availability Cheap	No interaction with WWTP treatment Low detection threshold On-line measurement No limitations due pH, conductivity and colour Some radiotracers are readily available and inexpensive
Disadvantage	Not suitable for colour, conducting liquids Stratification due to density difference Large threshold detection concentration Possible interference with WWTP treatment operations	Strict radiation safety regulations Relatively expensive detection equipment

Table 1c.Solid tracers.- *Field of applications: Collection networks, Sand and grit removal, Clarifiers, Biological reactors (aerobic and anaerobic), Discharge networks*

	Conventional Tracers	Radioactive Tracers
Tracers used	No known solid tracers Current method: sampling, filtering, drying, weighing	^{113m}In, ^{99m}Tc, ^{198}Au, ^{140}La, etc.
Advantage		Same as in case of liquid phase radiotracers Independent detection without interference with gas and liquid detection
Disadvantage	Tedious Difficult to get statistically representative sample	Strict radiation safety regulations Relatively expensive detection equipment

3.1. SELECTION OF RADIOTRACERS FOR INVESTIGATION OF WASTEWATER TREATMENT PLANTS

3.1.1. Type of radiotracers

Selection of a suitable radiotracer is very important for the success of every radiotracer experiment. Factors that are important in the selection of a radiotracer are given as follows:

- Physical/chemical form and properties of a tracer with respect to the material to be traced.
- Half-life of a tracer with respect to the theoretical MRT of the system to be investigated.
- Type and energy of radiation emitted with respect to the detection geometry (thickness of a wall)
- Method of measurement (sampling or in-situ measurement)
- Handling of radioactive materials, radiological protection/regulations.
- Availability and cost of tracer

A tracer has to be chemically identical with the substance to be traced when studying chemical reaction kinetics, solubility, vapor pressure, processes dominated by atomic and molecular diffusion, and others. Radioactive isotopes of the traced elements and labeled molecules are used as intrinsic tracers, for example, H^3HO for H_2O, $^{24}NaOH$ for NaOH or $^{14}CO_2$ for CO_2, etc.

When tracing water and solids in WWTP processes where no chemical changes occur, the radiotracer does not have to be chemically representative of the element or compound. For example, when water is being traced, the only requirement of the tracer is that it behaves as the water behaves under the conditions of the WWTP. Some of extrinsic radiotracers that have been successfully used in aqueous solutions are ^{51}Cr-EDTA, ^{113m}In-EDTA, Na^{131}I, K^{131}I, $^{24}Na_2CO_3$, $^{24}NaHCO_3$, $NH_4{}^{82}Br$, $H^{198}AuCl_4$ and $^{99m}TcO_4^-$. EDTA (ethylenediamine tetraacetic acid) embraces the tracer cation and shields it from negative charges present in environment that otherwise would somehow interfere in its tracer performance.

Extrinsic tracers widely used for tracing organic fluids are dibromobenzene ($C_6H_4{}^{82}Br_2$), ^{131}I-kerosene and iodobenzene ($C_6H_5{}^{131}I$), ^{113m}In in oleate or stearate form. Gas radiotracers commonly used are ^{41}Ar, ^{79}Kr, $H_3{}^{82}Br$ and ^{133}Xe. Surface labeled sand and silt with ^{198}Au, ^{113m}In, ^{51}Cr, ^{46}Sc and ^{175}Hf have been widely used in sediment transport studies in WWTP. Specially produced glasses containing elements that can be activated by (n, γ) reactions are used as sand tracers. ^{198}Au, ^{51}Cr, ^{192}Ir and ^{46}Sc are the radioactive nuclides often induced by neutron activation.

3.1.2. Radiotracers from radioisotope generators

Radioisotope generators are very important in radiotracer work in developing countries without nuclear reactors. There are three useful radioisotope generators for remote radiotracer applications mostly in liquid phase: ^{99}Mo/^{99m}Tc, ^{113}Sn/^{113m}In, ^{137}Cs/^{137}Ba. Only ^{99}Mo/^{99m}Tc, which is largely used in nuclear medicine, is available in the market with reasonable price. It has several applications in investigating various WWTP units and processes in laboratory, pilot and industrial scales.

^{113}Sn/^{113m}In generator can be found from few suppliers. The gamma-ray energy of 390 keV together with the useful half-lives of the ^{113}Sn parent (115 d) and ^{113m}In daughter (100 min) makes this generator suitable for some applications, in particular for solid phase tracing.

^{137}Cs/^{137}Ba generator produces very short live radiotracer but has practically very long life (several years at least). This is a useful radiotracer generator for routine service to end users, in particular for liquid flow rate measurement and flowmeter calibration in WWTP processing units, because of its high gamma energy which can be easily detected from outside pipes. The ^{137}Cs/^{137}Ba generator is not available in the market. There are some tracer companies that produce home-made ^{137}Cs/^{137}Ba generator for their own use.

Commercially available generators are generally eluted using aqueous liquids or diluted solution of HCl, so that the eluates are compatible with the water or water-like flows. Some typical applications of radionuclide generator-based radiotracers can be summarized as follows:

- ^{99m}Tc in sodium pertechnetate form: Water tracing in wastewater treatment plants for RTD measurement.
- ^{99m}Tc in reduced $SnCl_2$ medium: Sludge labelling-tracing in wastewater treatment plants for RTD measurements.
- ^{113m}In in chloride solution: Sludge labelling-tracing in wastewater treatment plants for RTD measurements.
- ^{113m}In in EDTA complex: Water tracing in various hydraulic pilot plants and laboratory facilities.

3.1.3. Radiotracers for water tracing

Tritiated water (H^3HO) is the only intrinsic radiotracer for water. One has to use it very carefully due to possible interfering exchange of ^{3}H with hydrogen in other molecules, evaporation, or exchange with atmospheric moisture. Measurement of ^{3}H requires sampling and laboratory measurements by liquid scintillation.

Gamma emitting tracers commonly used in water tracing are listed in Table 2:

TABLE 2. SOME WATER RADIOTRACERS

Isotope	^{137m}***Ba***	^{113m}***In***	^{99m}***Tc***	^{82}***Br***	^{131}***I***	^{46}***Sc***
Half-life	2.6 min	100 min	6.02 hours	1.5 days	8.04 days	84 days
γ Energy (keV)	662	410	140	≈ 700	360	900 and 1100
Obtaining	^{137}Cs/^{137m}Ba Generator	^{113}Sn/ ^{113m}In Generator	^{99}Mo/^{99m}Tc Generator	Reactor activation	Reactor activation	Reactor activation
Preparation	None	EDTA complexation	None	NH_4Br	KI or NaI	EDTA complexation

3.1.4. Radiotracers for solid tracing

Adsorption of a radiotracer on the surface of a solid has been used as a labeling method for many types of particles. For massive (i.e. non porous) particles such as sand, the labeling is proportional to the surface of the particle. This methodology is operational but we consider that it is not a convenient one. It is quite better to simulate sand by a glass containing an activable element. The activity of the particle will be in this case proportional to its mass. Fine particles such as mud or sludge, are very small and form aggregates (flocks). It is in this case possible to obtain mass labeling through the adsorption technology. Tables 3 and 4 present some radiotracers for labeling different kind of sludge's, in particular for fine particle silt and inert particle sand.

3.1.5. Radiotracers for gas tracing

Some gas tracers can be produced by direct neutron activation in nuclear reactors such as ^{41}Ar and ^{79}Kr (Table 5). Methyl bromide ($CH_3{}^{82}Br$) is produced through chemical synthesis of radioactive ^{82}Br.

TABLE 3. SOME RADIOTRACERS FOR FINE PARTICLE SLUDGE (SILT)

Isotope	^{113m}***In***	^{99m}***Tc***	^{82}***Br***	^{198}***Au***	$^{175-181}$ ***Hf***	^{160}***Tb***	^{46}***Sc***
Half-life	100 min	6.02 hours	1.5 days	2.7 days	45 days	73 days	84 days
γ Energy (keV)	410	140	≈ 700	410	Complex spectrum	Complex spectrum	900 and 1100
Obtaining	^{113}Sn/ ^{113m}In Generator	^{99}Mo/^{99m}Tc Generator	Reactor activation	Reactor activation	Reactor activation	Reactor activation	Reactor activation
Preparation	None	Reduction by $SnCl_2$	Chloride solution	Chloride solution	Chloride solution	Chloride solution	Chloride solution

TABLE 4. SOME RADIOTRACERS FOR SAND PARTICLES

Isotope	^{140}***La***	^{198}***Au***	^{52}***Mn***	^{147}***Nd***	^{192}***Ir***
Half-life	1.7 days	2.7 days	5.7 days	11 days	74 days
γ Energy (keV)	330 to 1600	410	730 to 1460	Complex spectrum	296 to 468
Obtaining	Reactor activation	Reactor activation	Reactor activation	Reactor activation	Reactor activation
Preparation	Glass powder	Glass powder	Glass powder	Glass powder	Glass powder

TABLE 5. SOME GAS TRACERS

Isotope	***^{41}Ar***	***^{76}As***	***^{82}Br***	***^{79}Kr***
Half-life	110 min	26.5 hours	36 hours	34 hours
γ Energy (keV)	1370	550 to 2020	≈ 700	136 to 830
Chemical form	Gas	AsH_3	CH_3Br	Gas
Obtaining	Reactor activation	Reactor activation	Reactor activation	Reactor activation

3.1.6. Required amount of tracer

After selection of a radiotracer suitable for a particular tracer experiment, the estimation of the radiotracer activity required to be used is the next important step in designing the radiotracer experiment The upper limit is set by radiological safety considerations, and oftentimes also by the capacity of the available irradiation facility and by cost considerations. The lower limit of the amount of tracer is estimated according to efficiency of the detection system, requested accuracy, dilution between injection and detection points, and background radiation level.

The best estimation of the required tracer activity for a radiotracer study implies the use of a mathematical model to simulate the theoretical output response of the tracer on the basis of several parameters of the WWTP unit to be investigated. However, this information is generally not available for the tracer specialist before the tracer test for RTD measurement.

When the mathematical model of a system is not available, simplified calculation method is used to have an idea about the amount of tracer to be injected. In maximum dilution method, it is assumed that the system is a perfect mixer, and the initial radiotracer concentration (C_0) at the output of the system is the ratio of the injected radiotracer activity to the system volume ($C_0 = A_0/V$).

It is recommendable to inject an amount of radiotracer (A_0) to get an initial radiotracer concentration equal to ten times of the lower detection limit or the minimal detectable concentration of the tracer (C_0 = 10 C_{min}).

$$A_0 = 10\, C_{min}\, V$$

In the case of a radiotracer, C_{min} depends on radiation background level, detection efficiency and counting time. For a 95% confidence limit, C_{min} can be delivered as following equation (Lloyd A. Currie: ‘Limits for Quantitative Detection and Quantitative Determination: Application to Radiochemistry’, Anal. Chem. 40, (1968) 586-593):

$$C_{\min} = \frac{2}{\varphi}\left(\frac{2\,R_B}{\Delta t}\right)^{1/2}$$

where R_B is background count rate, Δt is counting time, and φ is detection efficiency. Thus, the activity to be injected could be calculated using following equation.

$$A_0 = \frac{28}{\varphi}\left(\frac{R_B}{\Delta t}\right)^{1/2} \cdot V$$

The detection efficiency (φ) is defined as the response (counts·s^{-1}) of the detector to the unit specific activity (Bq/m^3) of the fluid inside the outlet pipe at a given detection geometry. Its unit is [$s^1 \cdot Bq^{-1} \cdot m^3$].

The detection efficiency can be measured experimentally by simulating the field experimental arrangement in the laboratory using a piece of pipe of the same diameter and wall thickness. The pipe is plugged at both ends and an injection port is installed on the pipe. The background count rate is measured at the beginning. The radiotracer with known specific activity is injected and the count rate is measured.

The detection efficiency can be calculated also theoretically using software based on Monte Carlo method. The ECRIN2 software can be used for this purpose. The software was developed by CEA in France and has been using in many radiotracer laboratories.

Example: The estimation of the activity needed for a radiotracer test in a system with volume of 1000 m^3. The radiotracer (Br-82) is injected as Dirac pulse at the inlet charging pipe and the radiotracer radiation is measured at the outlet discharging pipe (diameter 25 cm, wall) using a 2”× 2” NaI(Tl) scintillation detector.

Detection efficiency calculated using ECRIN2 software is 8.7×10^{-5} ($s^{-1} \cdot Bq^{-1} \cdot m^3$). Assume the background count rate is 100 cps and the counting time is 10 seconds. Then, the activity need to be injected is;

$$A_0 = 28/(8.7 \times 10^{-5}\ s^{-1} \cdot Bq^{-1} \cdot m^3) \times (100\ s^{-1}/10\ s)^{1/2} \times 1000\ m^3 = 10^9\ Bq\ (\text{or } 27\ mCi)$$

The needed activity calculated by this equation only represents an approximation, but it is good enough as a reference value. In practice, an activity of several time of this value is applied for obtaining higher accuracy.

3.1.7. Radiotracer injection system

There many possibilities of injection modes and devices, corresponding to the diversity of wastewater treatment processes and units, as well as of tracers. In a WWTP, however, most of tracers are in liquid form, while gaseous radiotracers are very seldom used. Solid tracers for WWTP investigation consist of fine labeled particles dispersed in water, and hence can be injected using liquid injection systems.

Liquid tracer injection systems range from exceedingly simple to rather complex schemes. Injecting a pulse of a radioactive tracer into the flow in an open channel is just pouring it from a bucket. Sometimes a long tong and a string are needed to position and overturn the bucket. A hypodermic syringe is also used when the volume of a tracer is small enough.

To minimize handling an open source (radiotracer) at the site of injection, special tools were developed. Fig. 19 shows an injection system in which a glass vial containing a liquid radiotracer can be crushed under the flow of a open channel. This injection system has following features:

- It minimizes the radiation exposure and contamination,
- Is operates easy,
- It discharges instantaneous the radiotracer into a process system.

For closed systems such as sludge digesters, a certain amount of liquid tracer should be injected against the system pressure. A typical example of remote control liquid injection systems is shown in Fig. 20. It operates by air pressure and can transfer a fixed amount of radiotracer directly from a radiotracer container to the system to be investigated.

A particular case occurs for sludge particles which have to be labeled and injected more or less simultaneously with a minimum action in order to warranty that their physico-chemical behavior is not modified by the labeling operation (Fig. 21).

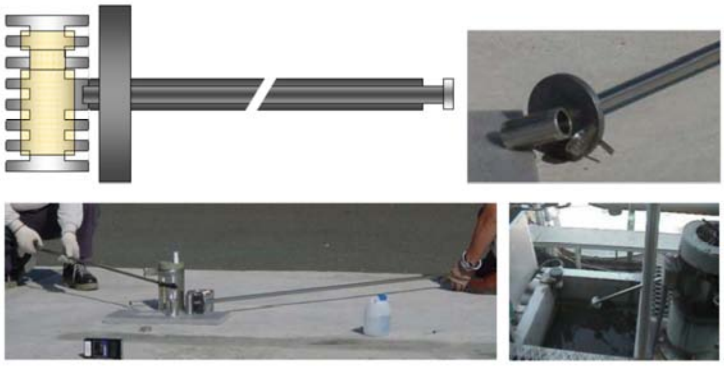


FIG.19. Liquid tracer injection tool for open channel.

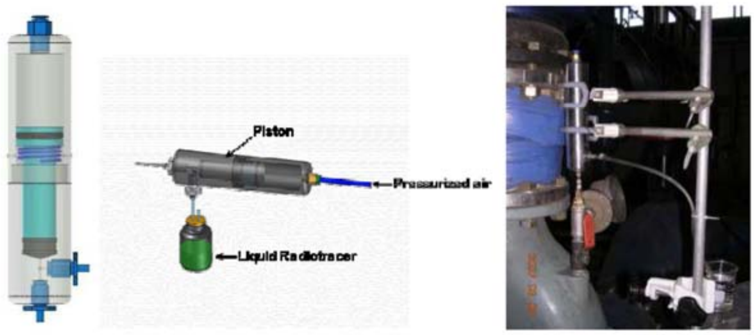


FIG.20. Remote control liquid tracer injector.

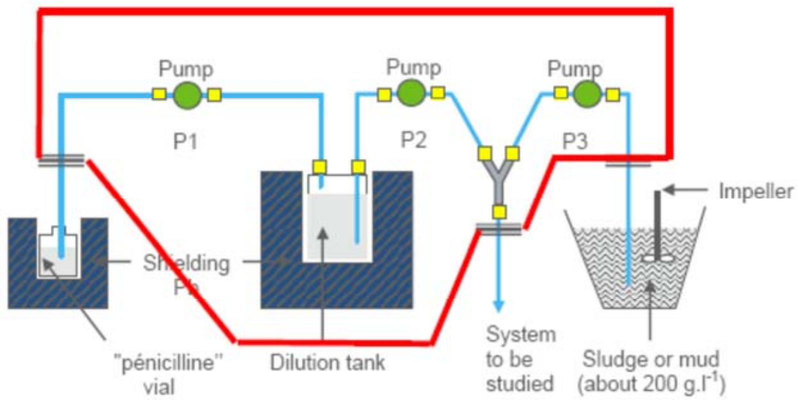


FIG.21. Scheme of a labelling/injection unit for sludge particles.

3.2. RADIOTRACER MEASUREMENT

3.2.1. Radiation detection

Generally on-line detection mode is the most competitive for radiotracer investigations in WWTP's units. Radiation detectors used for radiotracer measurement are generally two inches sodium iodide NaI (Tl) scintillation detectors coupled to a data acquisition system. Radiotracer once injected in the system can be monitored continuously (on-line) or by sampling (off-line). One of the advantages of the radiotracer for investigating opaque processes compared to other tracers is the possibility for on-line measurement, thus the online method has preference to sampling.

Since on-line radiotracer techniques involve most commonly only gamma-ray, the most common gamma-ray scintillator in use is the thallium- activated sodium iodide NaI(Tl) single crystal.

Two radiation detectors are needed for simple radiotracer RTD measurement, one at the inlet for recording the injecting pulse and the other at the outlet for measuring the experimental RTD response. More detectors (4-6) are needed for collecting additional comparative information in particular sites of the processing units, and as many as possible (> 10-20) are needed for complex engineering reactors. The most commonly used in field condition is NaI(Tl) detector in waterproof casting. It is very sensitive sensor for gamma radiation, for example a 1’’ × 1’’ NaI (Tl) scintillation detector for detection of ^{82}Br in water, in an infinite detection geometry condition, gives 65 cpm/kBq/m^3. Detection probes are mounted at selected locations at the inlet and outlet of the processing vessel and are shielded by lead collimators to protect them from the natural background and other parasite radiation may come from around. If needed, detectors are protected from heat (for temperature higher than 60-70^{0}C) by placing aluminum plate between the detector and reactor walls.

The data acquisition system (Fig. 22), which collects signals from several radiation detectors, is the basic equipment for online radiotracer RTD measurements. The data acquisition system ensures collection, treatment and visualization of the data. Dead time between two measurements is normally less than 1 µs. The visualization of data is as close as possible to ‘real time’ experiment. The measurements are simultaneous and the minimal dwelling time is 1-2 ms. Standard portable data acquisition systems for industrial radiotracer work are PC based data logger with unlimited possibility in the number of connected probes. There are several prototypes of data acquisition system (commercial or homemade). The most common probes consist of NaI(Tl) detectors in waterproof casting, preferably stainless steel. They are very sensitive sensors to gamma radiation, for example a 1’’× 1’’ NaI (Tl) scintillation detector for ^{82}Br measured in water with an infinite detection geometry condition gives 65 cpm/kBq/m^3.

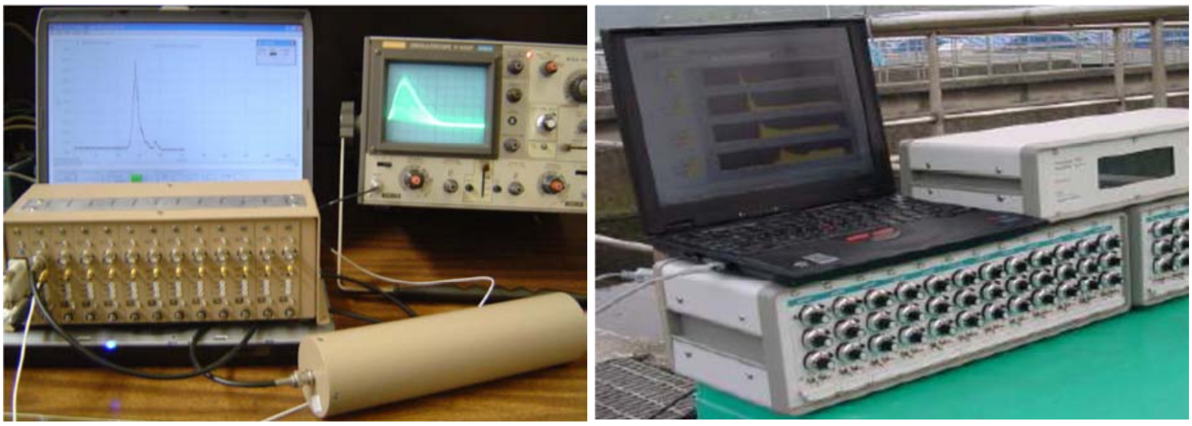


FIG.22. Data acquisition systems for online radiotracer tests.

The probes are placed (Fig. 23):

- 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,
- inside or around the tested vessel itself when it is possible,
- immerged inside the wastewater treatment units (different places and various depths),
- inside a portable detection chamber, where the sewer is pumped.

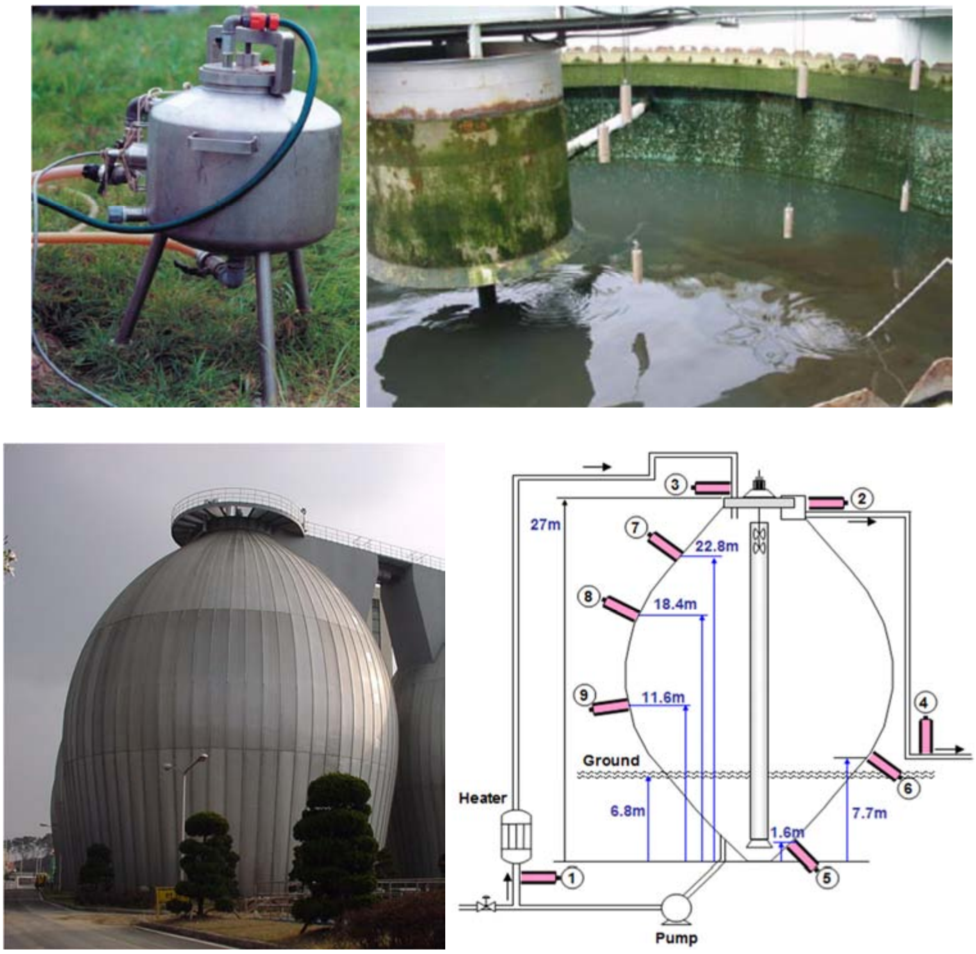


FIG.23. Examples of detection probe locations: inside the detection chamber; immerged in wastewater; on an anaerobic digester (9 probes placed at the inlet, at the outlet and around the system).

3.3. RADIATION PROTECTION AND SAFETY CONSIDERATIONS IN RADIOTRACER INVESTIGATIONS IN WASTEWATER TREATMENT PLANTS

Radiotracers emit ionizing radiations, which are potentially hazardous to health and therefore radiation protection measures are necessary throughout all stages of operations. Prescribed safety and legal regulations has to be followed during a radiotracer experiment.

For exposures from any source, except for therapeutic medical exposure, the doses, the number of people exposed and the likelihood of incurring exposures shall all be kept as low as reasonably achievable (ALARA principle). The design of a radiotracer experiment has to ensure optimization of radiation exposures. It should be emphasized that the most important aspect of dose limitation, assuming that the practice is justified, is to keep radiation doses as low as reasonably achievable.

The principles of dose limitation are briefly summarized below:

- no application of radiation should be undertaken unless justified,
- all doses should be kept ‘as low as reasonably achievable (ALARA principle)’, economic and social factors being taken into account,
- in any case, all individual doses must be kept below dose limits.

The optimization of radiation exposures primarily depends upon distance, time and shielding. The dose rate at a point is inversely proportional to the square of the distance between the source and the point. Therefore a radiation worker has to maintain maximum possible distance from a radiation source. The dose received is directly proportional to the time spent in handling the source. Thus the time of handling should be as short as possible. The radiation intensity at a point varies exponentially with the thickness of shielding material. Thus a radiation worker has to use an optimum thickness of shielding material against the radiating source.

The most elementary means of protection is known as 'TDS' or 'time, distance and shielding':

- Decreasing the time spent around a radiation source decreases the exposure
- Increasing the distance from a source decreases the exposure
- Increasing the thickness of shielding to absorb or reflect the radiation decreases the exposure

3.4. TYPICAL RADIOTRACER APPLICATIONS IN A WASTEWATER TREATMENT PLANTS

Radiotracer techniques are largely used in routine services for investigation of the hydrodynamics of wastewater in various processes and units of a WWTP. Possible radiotracers applications in most of the units are:

(a) Measurement of flow rates by radiotracer dilution method
(b) Mass balances.

The residence time distribution (RTD) method is common for many investigations in almost all processes. Radiotracers can be used for separate determination of RTD functions of liquid and solid phases and on the base of this information evaluation of mixing processes intensity. The separate labeling of solid particles provides the information concerning the sediment distribution in tank volume (zone of solid phase stagnation localization). The analysis of RTD functions indicate the presence or absence of short-circuit (by pass flow) and rate of active volume of tank.

The equalization tank has to ensure that all the incoming effluent is uniformly mixed (usually by air sparging) so that the outgoing effluent concentration is uniform. Since the size of these equalization vessels are large (several thousand m^3), radiotracer offers a unique opportunity to check the performance of the equalization tank by assessing its mixing characteristics, presence of dead (stagnant) zones and short circuiting. Experimental RTD response is analyzed using mathematical models to asses the efficacy of the equalization tank.

The volume of clarifier, $V[m^3]$ and the flow rate of water $Q[m^3/h]$ have to be optimized for obtaining the wastewater residence time sufficient for sedimentation process realization (appropriate relations between horizontal components of water flow velocity and vertical velocity of sedimentation).

Radiotracer can be used for determination of liquid and solid phases flow structure. The RTD function of both phases give a possibility to calculate the mean residence times of water and the sediment, evaluate the rate of dead and active volume of tank, and propose the appropriate flow model.

Radioactivity mass balance (for solid phase mass balance) and RTD (for liquid flow -mixing, dead zone and short circuiting – characteristics) are most ideal methods to evaluate the performance of various designs of clarifier under a variety of operating conditions (flow rate, mean residence time and solid flock concentrations).

After the primary clarifier the wastewater, if it is to be discharged, are directed to sand filter station, where additional process of solid particles removal take place.

Different types of sand filters i.e. fixed media or fluidized media are used and their performance in terms of the efficacy of solid-liquid separation can also be evaluated using radiotracers. The radiotracers can be used for identification of the presence of unfavorable water channeling effect.

Different radiotracers (for liquid and settling solids) can be used in clarifiers to asses the liquid phase RTD (water retention time) and the solid (flocks) phase axial concentration profile (degree of settling of the solids). A continuous monitoring of the radioactivity associated with the settled solids taken out from the bottom and the solids carried over through the overflow allows estimating the efficacy of the classifier as a sedimentation device. Radioactivity mass balance (for solid phase mass balance) and RTD (for liquid flow -mixing, dead zone and short circuiting – characteristics) are most common used methods to evaluate the performance of various designs of clarifier under a variety of operating conditions (flow rate, mean residence time and solid flock concentrations).

Because of the large residence times required to synthesize substantial quantity of the gas, the volume of digesters is in the range of 5000 to 20000 m^3. This is a classical 3 phase system of large dimensions and hence radiotracers (individually) can be used, similar to that used in clarifier to get information of the gas, solid and liquid phase fractional hold-ups, their spatial distribution, their movement and the mean residence times.

4. CASE STUDIES

Wastewater from industry and urban sites has to be treated before discharging to the river or sea. In all wastewater treatment units, such as mixer- distributor, clarifier- equalizer, biological, primary and secondary settlers, sedimentation tanks, a strong interdependence between hydraulic and technological phenomena is observed. All these units represent multiphase flow systems liquid-solid or liquid-solid-gas.

The tracer residence time distribution (RTD) method is basic for investigation of all the wastewater treatment units. The experimental RTD curve and its model provide many important parameters such as:

- mean residence time ;
- mean flow velocity;
- dead volume.

Examples of radiotracer applications for investigations of wastewater treatment units, such as equalizer- clarifier, mixer- distributor, aeration tank and rectangular and circle settlers are presented below.

4.1. RADIOTRACER INVESTIGATION OF WASTEWATER CHLORINATE PROCESS

Chlorine is normally used for water disinfection. The chlorine reactor consisted of two cylindrical reservoirs connected in series with volumes of $V_1 = 925\ m^3$ and $V_2 = 1625\ m^3$ (Fig. 24).

The main problem suspected was the low efficiency of wastewater chlorinate process. It was assumed the generation of preferential (short circuiting) flows and the creation of dead volumes. The purpose of the radiotracer tests was to diagnose the water phase hydrodynamic, to find out the actual model of transport (plug flow model was preferred), to evaluate the reactor efficiency and probably to optimize it. There were performed two radiotracer tests, a first as it was, and the second on after modification of reservoirs design (installation of baffles). ^{99m}Tc radiotracer (2.2 GBq) was used for each test. The mean residence time of water flow across both reservoirs was estimated of several hours. The experimental RTD curves and their models are shown in Fig. 25.

The experimental RTD curve of first test in existing condition was better approached by the model of two perfect mixers in series (J = 2) with some exchange with stagnant volume. The stagnant volume was estimated of 2-3 %, so rather small for affecting the performance and efficiency of the existing reactor. The experimental RTD curve did not show up any short-circuiting but the existing design model (almost perfect mixer J = 2) provides for rather bad and non-uniform micromixing of water with chlorine because of very large range of water residence times, so the purifying process was not efficient.

Installation of baffles inside the reactor was proposed to remediate the situation and improve the efficiency. The radiotracer test after installation of baffles showed a symmetrical experimental RTD curve (Fig. 25, right). The perfect mixers in series model was applied again but in this case the number of perfect mixers resulted of J = 20, that means the water is moving almost as plug flow. The micromixing is improved and consequently the efficiency of disinfectation was considerably increased.

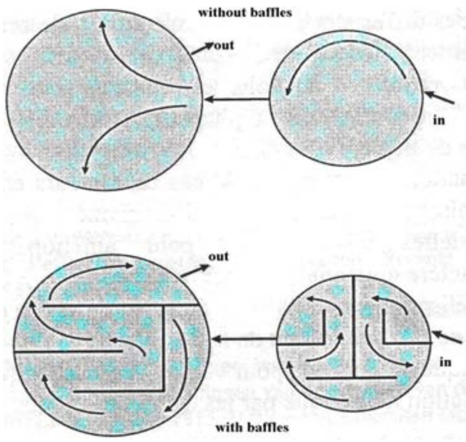


FIG.24. Reactor of water chlorification: before modification (up); after modifications (down).

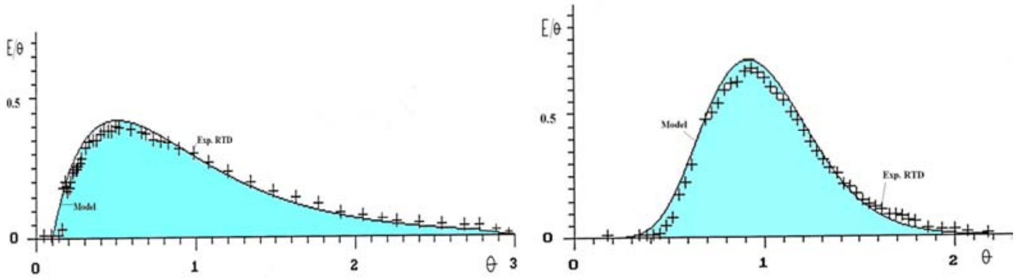


FIG.25. Experimental RTD curves and their models before(left) and after (right) modification.

4.2. RADIOTRACER INVESTIGATION OF EQUALIZER – CLARIFIER TANK

Many wastewater treatment plants utilize continuous equalization tanks, which are intended to equalize chemical composition and volume flow rate of wastewater. They are located upstream of biological and chemical facilities. Quite often are used combined equalizer-clarifier units that simultaneously with equalization realize sedimentation as well. Effectiveness of purification process carried out in equalizer – clarifier strongly depends on flow pattern of wastewater and sediment.

A combined equalizer-clarifier unit was experienced low performance. The wastewater was charged into this unit by a vertical pipe near the tank wall and discharged by system of two immersed perforated pipes (number of holes n = 160) on the tank circumference. The volume of tank was V = 5000m^3, the diameter D = 40 m, and flow rate q = 230 m^3/h. The radiotracer technique was used to diagnose the combined equalizer – clarifier unit.

The experimental RTD curve was obtained using radiotracer for the water liquid phase. Br-82 ($T_{1/2}$ = 36 hours) with total activity 3.7 GBq in the form of KBr aqueous solution was used to tracer the water component. The tracer was injected instantaneously at the tank input. Output signal was measured by waterproof scintillation probe immersed in the outlet wastewater stream.

Figure 26 shows the equalizer-clarifier unit of a wastewater treatment system where the radiotracer tests were conducted to investigate the homogenization and sediment removal efficiencies. The experimental RTD curve is shown in Fig. 27.

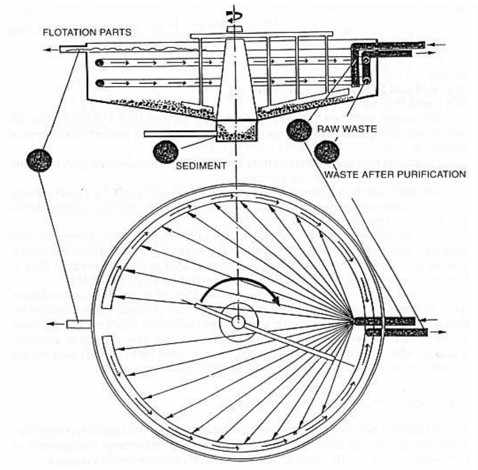


FIG.26. Scheme of equalizer-clarifier tank.

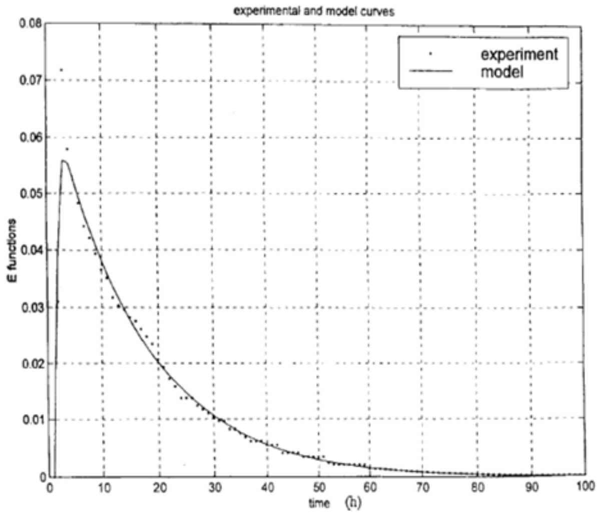


FIG.27. Comparison of experimental and model RTD functions.

The experimental RTD curve was modeled with a perfect mixer (J = 1.1). The experimental MRT (mean residence time) was found as T_{exp} = 15.7 h, when the theoretical MRT is calculated as T_{theor} = V/Q = 5000/230 = 21.7 h: Thus, the dead volume $V_d = 1 – V_{exp}/V_{theor}$ = 28%.

4.3. RADIOTRACER INVESTIGATION OF MIXER- DISTRIBUTOR UNIT

One of the most important unit operation used in wastewater treatment installation is mixing. It is used generally for homogenization of materials before their treatment in further principal units (reactors, aerated biological tanks, etc.). The mixing process can be realized, depending on specific applications, in mixers with mechanical rotating devices or by jet of liquid. The jet mixers have some advantages:

- no moving parts inside the mixer,
- low cost of maintains, construction and operation,
- low energy consumption.

There are not universal rules and correlations concerning the designing of these kinds of mixers for different geometries, flow rates and flow condition. The practice and experimental data are the sources of knowledge about this type of mixers.

An industrial continuous multi-jet mixer in a petrochemical factory was investigated using radiotracer method. Wastewaters were originated from four sources:

- petrochemical processes wastewater – S1
- petroreffinery processes wastewater – S2
- rainfall, cleaning of installations, technological and cooling water from petrochemical and petrorafinery parts of factory (systems S3 and S4).

All these wastewaters, which differ strongly by their chemical composition (COD, organic compounds contents, total sediment contents) and flow rates, were collected and treated together in four biological reactors R1, R2, R3, R4. To perform efficiency the biological reactors request uniformity of chemical composition at the input of each reactor. For this purpose the wastewaters form four sources S1÷S4 were mixed in special cylindrical jet mixer- distributor before transported to four R1÷R4 biological reactors. Poor performance of biological reactors was observed. It was assumed that the reason was the poor performance of cylindrical jet mixer.

The principal scheme of cylindrical jet mixer-distributor with volume V = 28.5 m^3 and diameter D = 2.5 m is shown in Fig.28.

Radiotracer was injected in each of streams S1, S2, S3 and S4. Four probes were placed at the exits of jet-mixer (entries of the four reactors R1-R4). Experimental RTD curves for S2 and S3 are shown in Fig. 29.

The shape of RTD function indicates clearly the bypass of liquid is jets S2 and S3. To improve mixing efficiencies a new mixer was designed. A tracer test was performed again. The experimental RTD curve obtained at the exits of S2 and S3 presents a regular curve (Fig. 30) that indicated the normal performance of the jet-mixer.

4.4. RADIOTRACER INVESTIGATION ON A SAND FILTER OF WASTEWATER TREATMENT PLANT

A sand filter operating in a WWTP was investigated with radiotracer. The filter was filled with gravels of 0.4 m height and sand of 0.7 m; the difference was occupied by wastewater. The tracer investigation aimed to find the wastewater flow model through the system and the volume occupied by sand and gravel.

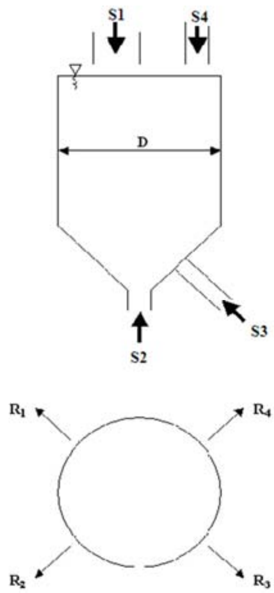


FIG.28. Scheme of jet-mixer (S_1÷S_4 sources of water, R_1÷R_4 streams feeding the biological reactors).

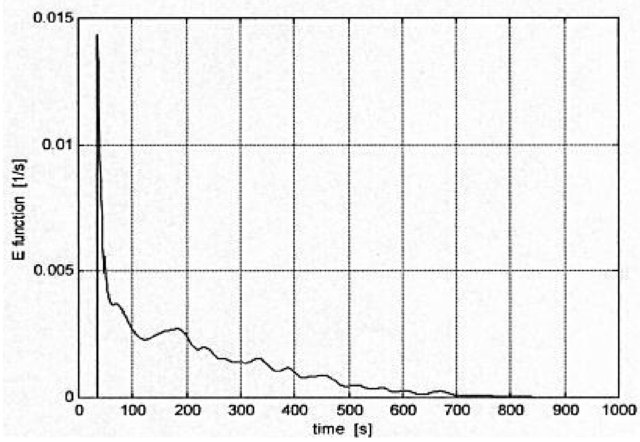


FIG.29. Exp. RTD of S2 and S3 jet mixer (Volume V = 28,5 m^3, flow rates Q_2 = Q_3 = 200 m^3/h).

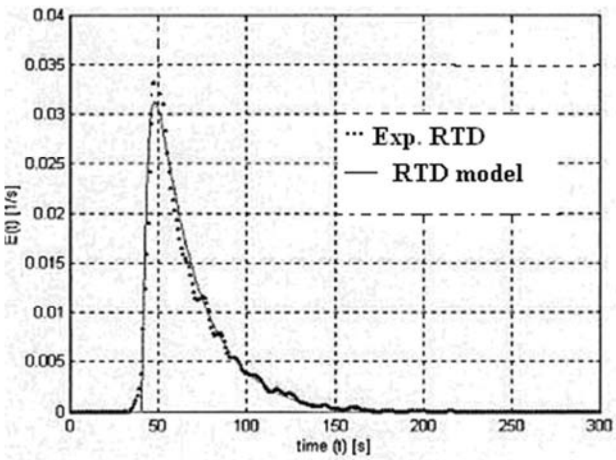


FIG.30. Comparison numerical and model RTD functions.

Indium-113m produced from a portable Sn/In generator was used as radiotracer. The indium chloride ($^{113m}InCl_3$) provided by the generator exists in the form of a positively charged ion that tends to be absorbed onto particles; thus it is one of good tracers for flocks (and sediments). By chelating with the EDTA ^{113m}In forms a complex compound (^{113m}In-EDTA), which is very stable to be used as water tracer without further reaction with environment. ^{113m}In-EDTA (1.11 GBq) was used as water tracer to investigate the flow dynamics of wastewater through the sand filter system.

As shown in the Fig. 31, ^{113m}In-EDTA was injected just before the pump guiding wastewater into the sand filter. Two radiation detection sensors (D1 and D2) were placed at the inlet and outlet of the sand filter, respectively to measure the tracer response curves. The experimental RTD curve was measured at the exit of the sand filter (detector D2 in Fig. 31). It showed a typical curve of two perfect mixer tanks in series (J-2) with a normal tail. The experimental MRT was found of 747 s.

Detectors D0 and D1 were placed on the wastewater guiding pipe to measure the liquid flow rate by transit time method. The data from these two detectors was used to precisely measure pumping rate. During the tracer experiment, the flowrate meter of the pump indicated 46.5 m^3/hr but it was turned out to be 30.4 m^3/hr from the radiotracer experiment. Taking account the volume of the sand filter of 9 m^3, the theoretical MRT of 1065 s. The measured mean residence time of 747 s showed that only 70% of the physical volume was occupied by water. The results of the test showed the normal functioning of the sand filter system, there was not observed any channeling through the sand filter.

4.5. DIAGNOSIS OF THE SUBMERGED BIOLOGICAL CONTACTOR

Radiotracer test was carried out to diagnose a submerged bioreactor, in particular to evaluate the flow behavior and its efficiency. The system consisted of six compartments, two bigger and four smaller. It was a part of a pilot plant for dye wastewater treatment using electron beam irradiation. Approximately 20 mCi (0.74 GBq) of ^{131}I tracer was injected into the system and seven radiation detectors were placed in six compartments and at the inlet and the outlet (Fig. 32).

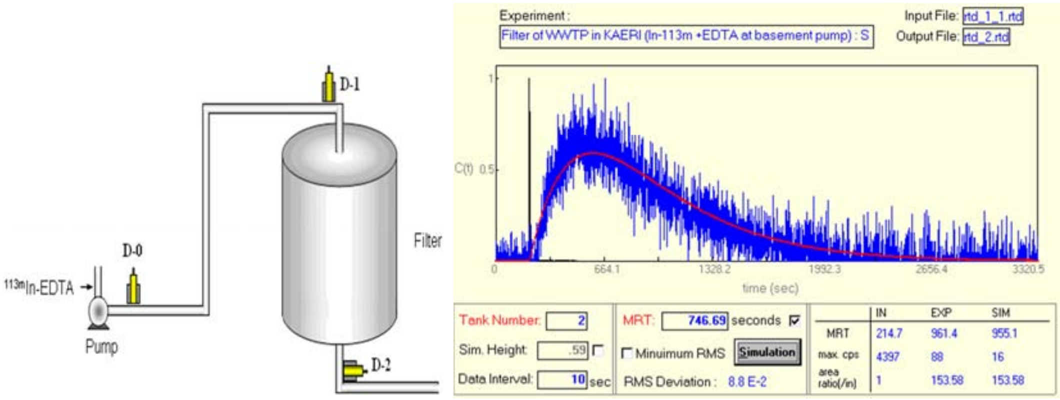


FIG.31. Diagram of radiotracer experiment on a sand filter and the RTD curve.

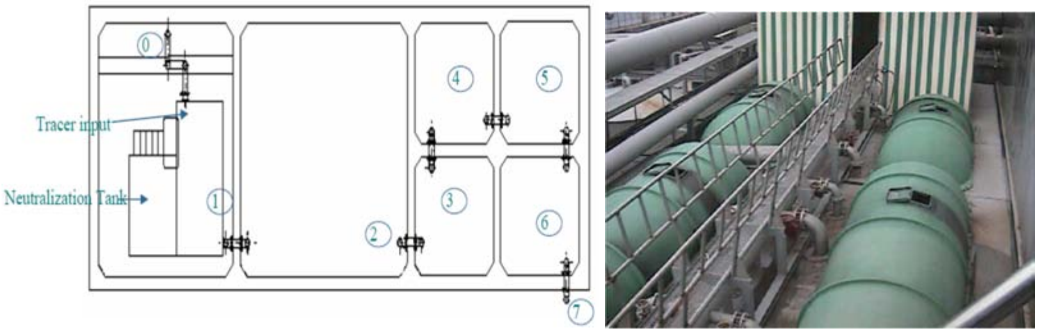


FIG.32. Submerged biological contactor and detector positions.

The experimental RTD curves for each compartment are shown in the Fig. 33 (normalized to curve amplitudes). The experimental RTD curves were modeled for each compartment. The first compartment model approached a perfect mixer with exchange with stagnant zone, whereas other five compartments were considered as perfect mixers (Fig. 34). Because the experimental RTD curve at the exit was not complete, this compartmental model was used to simulate and extrapolate the experimental data till end of the process. The fitting of experimental RTD curve with the model for the whole bioreactor resulted satisfactory (Fig. 35).

The experimental MRT of the whole system was calculated of 17 hours, where the designed MRT was of 22.3 hours, which means that 24% of the contactor volume was not active. The simulation of experimental results by the selected model indicated that in the first compartment a quarter of its volume was performing not efficiently as stagnant zone.

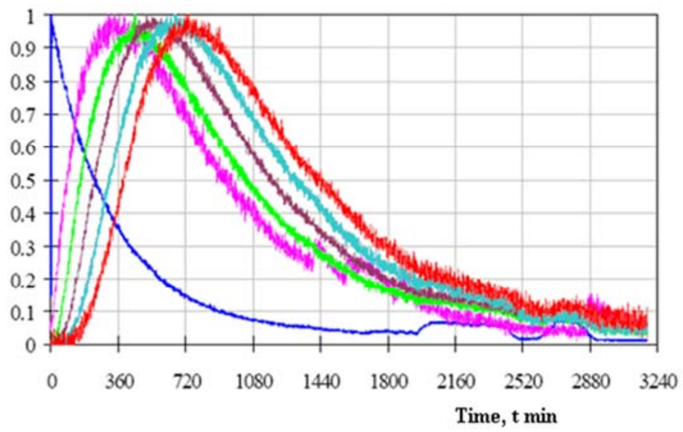


FIG.33. Experimental RTD curves measured at each compartment.

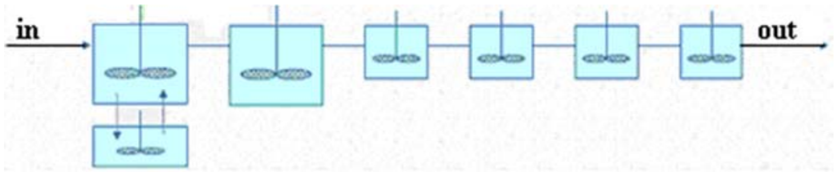


FIG.34. Model of the flow in the whole bioreactor.

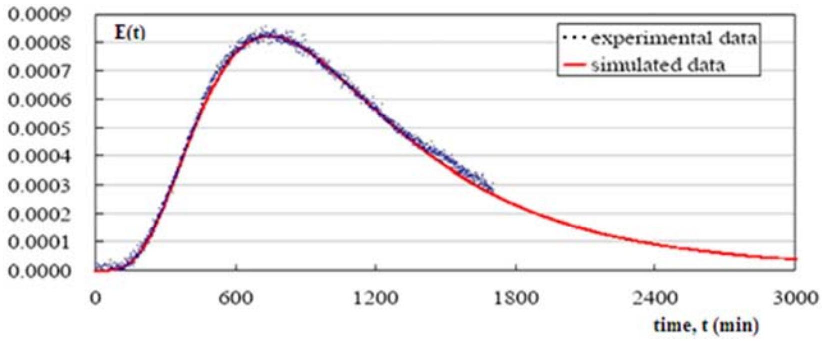


FIG.35. The model and the experimental data for the whole bioreactor.

The cumulative RTD function F(t) was calculated for each compartment from simulated experimental RTD curves (Fig. 36). The F(t) function specifies the traced material flowing out the tank after the time t. This function provides also the sampling time at the outlet of each tank for the same irradiation regime. This was an important parameter of the whole irradiation facility for performing representative samplings after every change of operational condition of the electron beam accelerator. Representative samplings were necessary for reliable data of the treatment process efficiency and scaling up the pilot plant results.

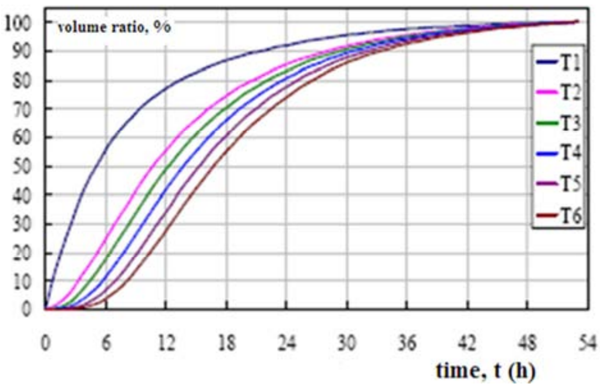


FIG.36. Calculation of the sampling time (flowing out time) in each tank.

The results of the radiotracer tests helped the designer of the wastewater treatment irradiation plant to schedule suitable sampling times for each compartment in function of the irradiation operation conditions.

4.6. RADIOTRACER INVESTIGATIONS OF PRIMARY CLARIFIER, AERATION TANK AND SECONDARY CLARIFIER

The scope of radiotracer study was to analyze the flow structure in operational units of Wastewater Treatment Plant (WWTP) in Islamabad in order to improve the efficiency and economize the performance of the processes.

The WWTP comprises of three main units:

- Primary clarifier;
- Aeration tank
- Secondary clarifier.

The design of primary and secondary clarifiers with a scraper sludge removal is shown in Fig.37, including indication of localization of scintillation detectors during experiments.

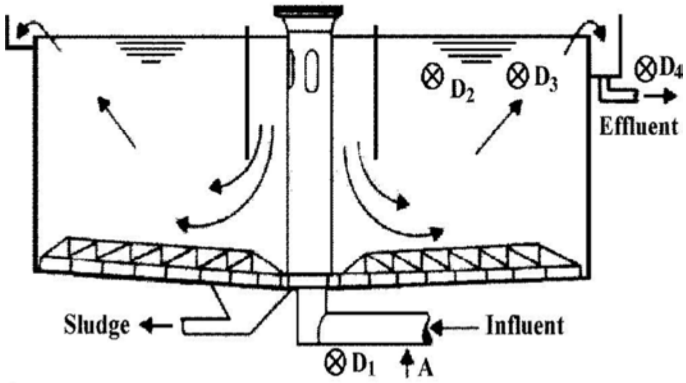


FIG.37. Design of center feed circular clarifier, A – tracer injection, D1-D4 – radiation detectors.

The design (top view) of the aeration tank is given in Fig. 38. It consists of five equal chambers connected by perforated baffles with no constrained flow near bottom and free surface. Air is feeding by perforated pipes located in the central region of the tank.

1. Radiotracer tests

Radiotracer Br-82 as aqueous potassium bromide ($K^{82}Br$) with an activity 2 GBq was used as tracer for investigation of various units of WWTP. The radiotracer was injected instantaneously (Fig.39). Four signals (input, output and two signals from detectors immersed in water, located on bridge of scraper) for the clarifier and two in the aeration tank were registered by the multipoint measuring system Minekin 9301. The step of time discretization was 1 min per channel.

2. Results

(a) Primary clarifier

The experimental RTD curve obtained at the output of the primary clarifier (probe D4) and its model are shown in Fig. 40.

The RTD software package (DTS PRO version 4.20) was used for treatment and modeling of the experimental data. Fig. 41 shows the selected model of primary clarifier, which fits better with the experimental RTD curve (Fig. 40).

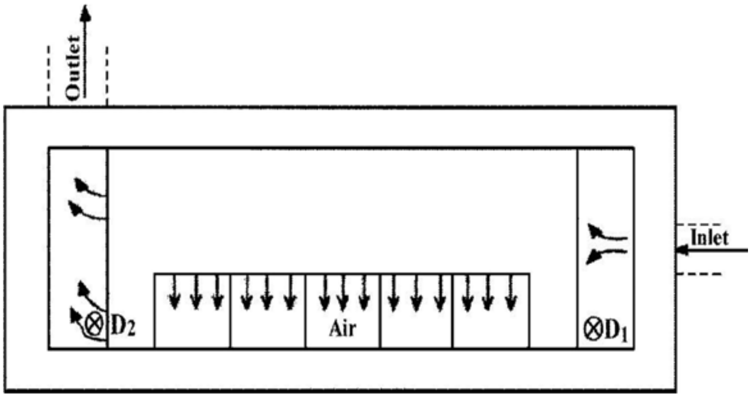


FIG.38. Design of aeration tank, D1-D2 – radiation detectors.

FIG.39. Radiotracer injection in the primary clarifier.

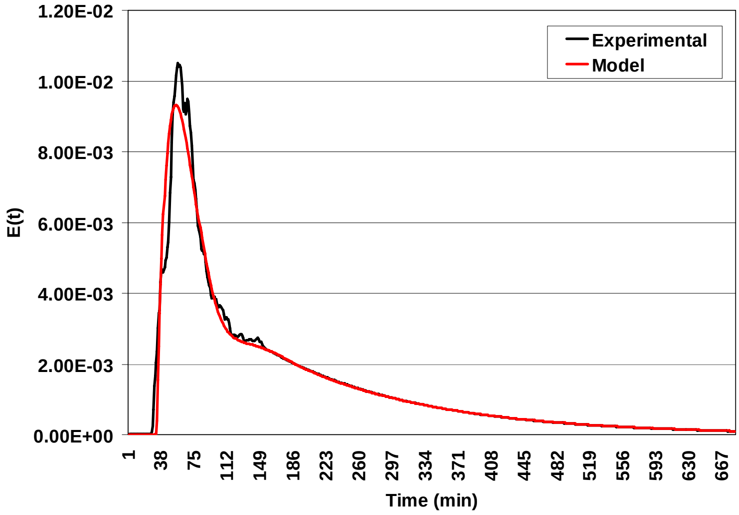


FIG.40. Experimental and model RTD curves of the primary clarifier.

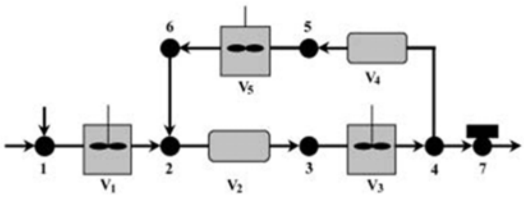


FIG.41. Model of the primary clarifier. V_1 = 96.2 m^3, V_2 = 285.78 m^3, V_3 = 201.8 m^3, V_4 = 76.3 m^3, V_5 = 199 m^3

Where: V1, V3 and V5 are perfect mixing cells and V2 and V4 are plug flow reactors.

From the inlet node the flow behaves like passing through a small perfect mixing cell and reaches the center of the clarifier. From node no. 2 to node no. 4, the flow is through a perfect mixing cell connected with the plug flow reactor. Then there is a recycle between node no. 2 and node no. 4 (with a ratio of 0.87) through the perfect mixing cell connected with the plug flow reactor.

Experimental and model output responses of the primary clarifier (Fig. 40) show a high peak at 57 min and another small peak that appears later at 147 min. The first peak is due to the short-circuit that causes a great reduction in the removal efficiency of the settling tank.

The second peak indicates the main flow inside the primary clarifier. The mean residence time of the model curve was calculated from the moment of first order of the model curve and it is 165.7min, i.e. very near to the experimental value of the mean residence time.

The volume of the primary clarifier was V1 = 1387 m^3 and the volumetric flow rate was 4.8±0.15 m^3/min that gives the theoretical mean residence time of 289 minutes. The experimental mean residence time of the primary clarifier was estimated as 164.3 min. It means that the system has approximately 43% dead volume.

(b) Aeration tank

The experimental RTD curve obtained at the outlet of the aeration tank (probe D2) is shown in Fig. 42. The best model found using RTD software is shown in Fig. 43.

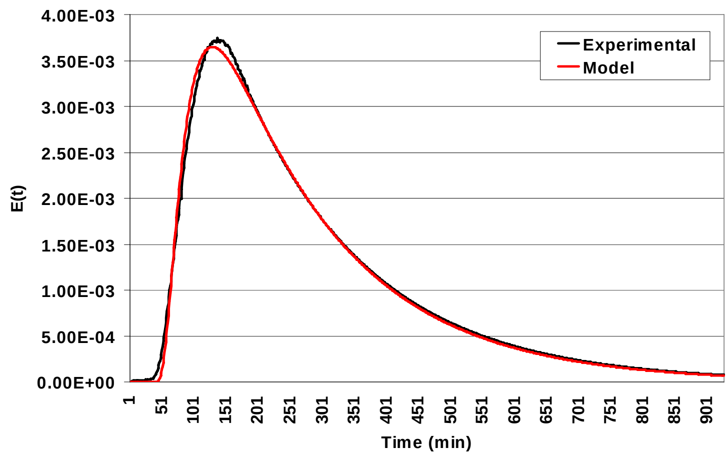


FIG.42. Experimental and model RTD curves of the aeration tank.

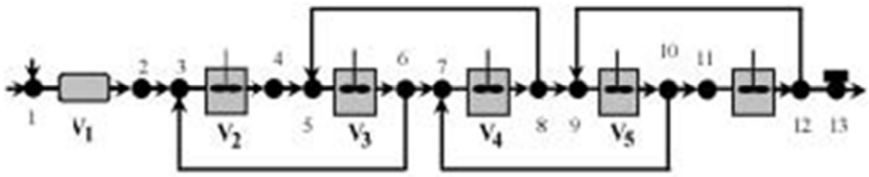


FIG.43. Model of the aeration tank. V1 = 80 m^3, V2 = 101 m^3, V3 = 100 m^3, V4 = 100 m^3, V5 = 97.7 m^3, V6 = 106.7 m^3.

The model consists of five perfect mixers in series with back mixing and connected with a plug flow reactor at the beginning. After the injection point, the incoming wastewater passes through a narrow duct before it enters into the series of tanks through small holes. Because of this reason, a plug flow reactor is used between node no. 1 and node no. 2. Back mixing ratio of the tanks connected in series is found to be 2.7.

The volume of the aeration tank was 567.5 m^3 and the volumetric flow rate during the experiment was 2.08 ± 0.08 m^3/min. It gives the theoretical mean residence time of 272.8 min. The experimental mean residence time of the unit was estimated as 271.9 min with a very small dead volume (0.32%). Therefore, almost negligible amount of dead volume was estimated in the aeration tank. This is due to the vigorous mixing process inside the aeration tank.

Due to high gas flow rate, tracer experiments conducted in aeration tank have shown that water and sludge have generally similar flow behavior. Radiotracer investigation in aeration tank has shown that the fluid flow can be modeled either by perfect mixing cells in series or by perfect mixing cells in series with back mixing. The number of mixing cells found by RTD modeling was J=5, in fact number J is a function of both gas and water flowrates as well as of the geometrical configuration. The results of this experiment showed that the aeration tank was achieving the designed residence time and was working efficiently as far as residence time is concerned.

(c) Secondary clarifier

The experimental RTD curve obtained at the output of the secondary clarifier is given in the Fig. 44. Figure 45 shows the best model found using RTD software simulation.

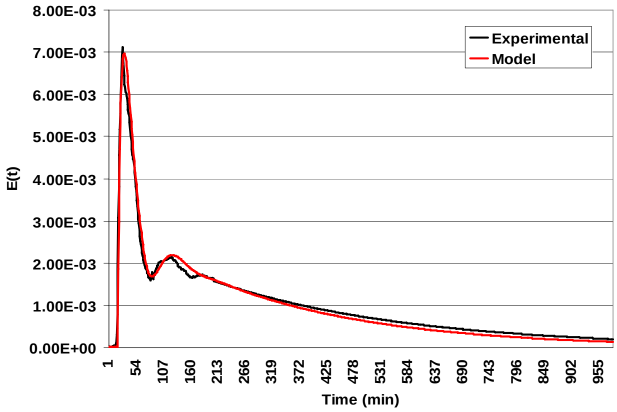


FIG.44. Experimental and model RTD curves of the secondary clarifier.

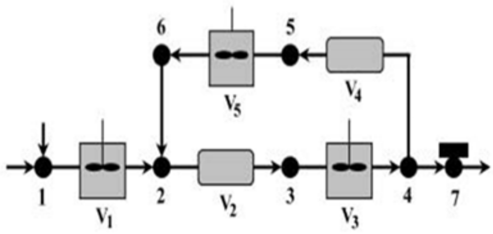


FIG.45. Model of the secondary clarifier.
Where: V1 = 29 m^3, V2 = 230.2 m^3, V3= 374 m^3, V4 = 314.1 m^3, V5 = 315 m^3.

In the model, node no. 1 is the inlet and tracer input, node no. 7 is the outlet; V_1, V_3 and V_5 are the perfect mixing cells and V_2, V_4 are the plug flow reactors. From the inlet node, the flow goes through a small perfect mixing cell in the center of the clarifier. From node no. 2 to node no. 4, the flow is through the perfect mixing cell connected with the plug flow reactor. Then, there is a recycle between node no. 2 and node no. 4 (with ratio 2.3) through the perfect mixing cell connected with the plug flow reactor.

Experimental and model output responses of the secondary clarifier (Fig. 44) show a sharp high peak at 27 min indicating that an important portion of the tracer passes away due to the short-circuiting causing a significant reduction in the removal efficiency of the settling tank. There is another peak appearing at 124 min, which is representing the main flow of the secondary clarifier. The mean residence time of the model curve is calculated from the moment of first order of the model curve and it is 260.2 min that is close to the experimental value of the mean residence time.

The total volume of the secondary clarifier was 2790 m^3 which is almost double that of the primary clarifier. The volumetric flow rate during the experiment was 4.16 ± 0.15 m^3/min giving the theoretical mean residence time of 670.6 min. The experimental mean residence time of the secondary clarifier was estimated as 284.7 min. The dead volume of the system was estimated as 57.5%. This shows that the working efficiency of the unit is very poor because more than half of the system volume was not taking part in the process. All final results are summarized in Table 6.

TABLE 6. SUMMARY OF RESULTS OBTAINED BY RADIOTRACERS.

System under investigation	Volume (m^3)	Flow rate (m^3/min)	Theoretical MRT (min)	Exp. MRT (min)	Dead Volume (%)
Primary clarifier	1387	4.83	287	164	43
Aeration tank	567.5	2.08	272	271	0.2
Secondary clarifier	2790	4.17	670	285	57

3. Conclusions

- The aeration tank behavior was normal. The model consisting of five perfectly mixing cells in series fits well with the design.
- The primary and secondary clarifiers had large dead volumes. Necessary remedial action was required to be taken by the plant operator in this regard.

4.7. RADIOTRACERS FOR DIAGNOSING THE PERFORMANCE OF A SECONDARY CLARIFIER

Radiotracer tests were used to diagnose the performance of a secondary clarifier (Fig. 46). Characteristics of the clarifier were:

- Diameter 23.6 m
- Surface 437 m^2
- Volume 1000 m^3

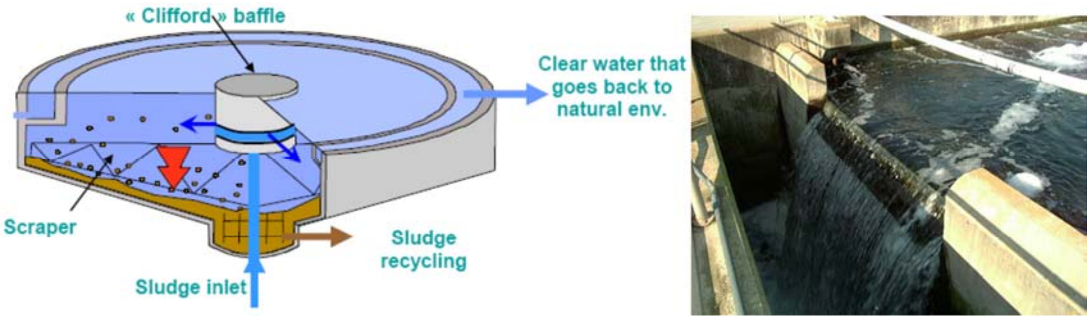


FIG.46. Scheme of the secondary clarifier.

The objectives of radiotracer tests were:
- study of the behavior of water and solid phases for different conditions of sludge bed and recirculation flow-rate
- validation of a CFD model.

Seven radiotracer tests were conducted:
- Water tracing experiment : 2 tests
  - tracer : Tc-99m, 50 mCi (1.85 GBq)
  - recycling flow rate 250 m^3/h
- Sludge tracing experiment : 5 tests
  - tracer : Au-198 , 50 mCi (1.85 GBq)
  - 3 conditions of the sludge bed
  - 2 recycling conditions 250 and 500 m^3/h

The injection point was at the outlet of the aeration channel which is the inlet of the clarifier. The location of the detection probes was:

- 9 probes (D1 to D9) were placed on the rotating arm of the scrapper (1 turn/30 min) (Fig. 47)
- 1 probe (D10) was placed inside the Clifford baffle at the entrance of the clarifier
- 1 probe (D11) was placed on the recirculation circuit
- 1 probe (D12) was paced at the water outlet of the clarifier (discharge to the river).

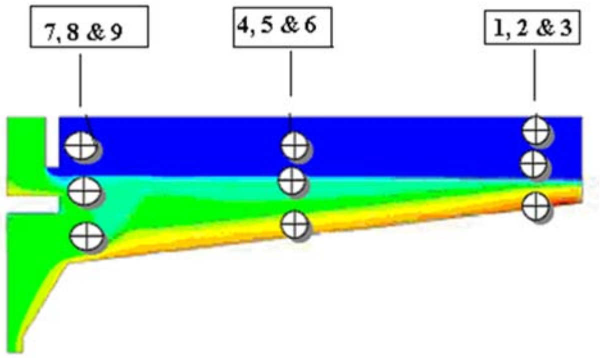


FIG.47. Positions of the 9 probes inside the secondary clarifier.

- Probes D1, D2 and D3 were located 9.85 m from the rotation axis of the clarifier, in heights 0.30, 0.80 and 1.30 m respectively, above the clarifier slope.
- Probes D4, D5 and D6 were placed 6.35 m from the axis, in heights 0.25, 1.10 and 1.60 m respectively, above the clarifier slope:.
- Probes D7, D8 and D9 were installed 3.15 m from the axis, in the heights 0.25, 1.60 and 2.00 m respectively.

Examples of experimental response curves for sludge experiment are shown in Figs. 48-50. Figures 51-53 compare experimental response curves obtained by radiotracer with CFD models.

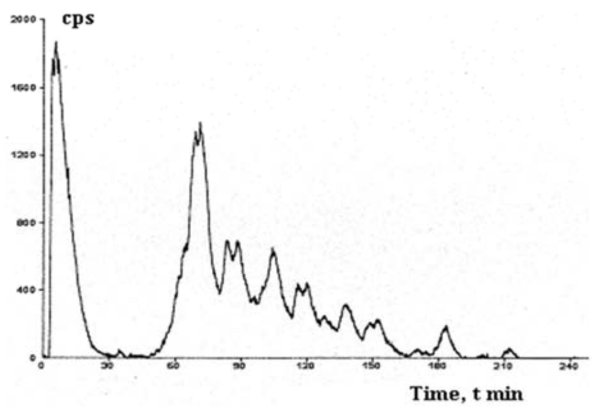


FIG.48. Experimental response curve obtained by probe D11 on the recirculation loop.

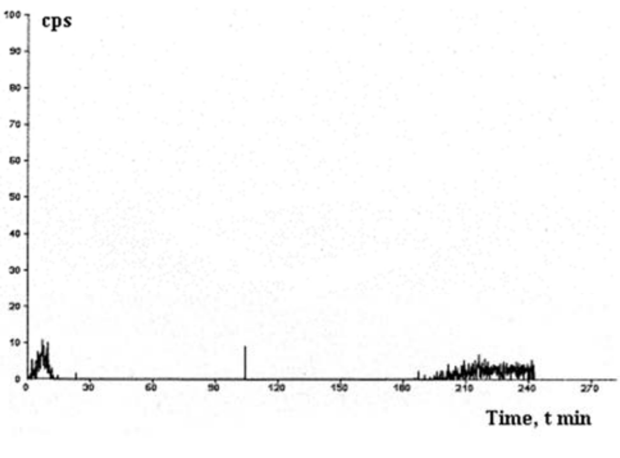


FIG.49. Experimental response curve at outlet to river obtained byprobe D12.

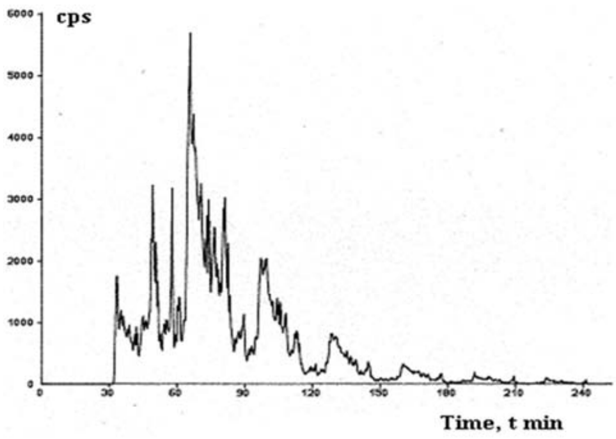


FIG.50. Experimental response curve obtained by probe D1 (distance to axis 9.85 m, height 30 cm).

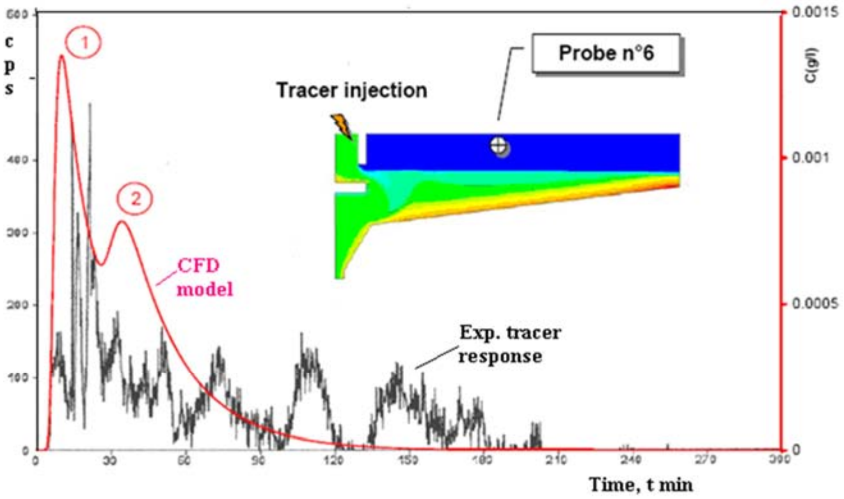


FIG.51. Comparison between CFD model and radiotracer experiment – Probe D6.

Results:

- Time of arrival of the flock = 4.5 min after the sludge entrance,
- No more signal after 150-180 min, meaning the region is only clarified water,
- Sludge concentration peak n°1 around 20 min.

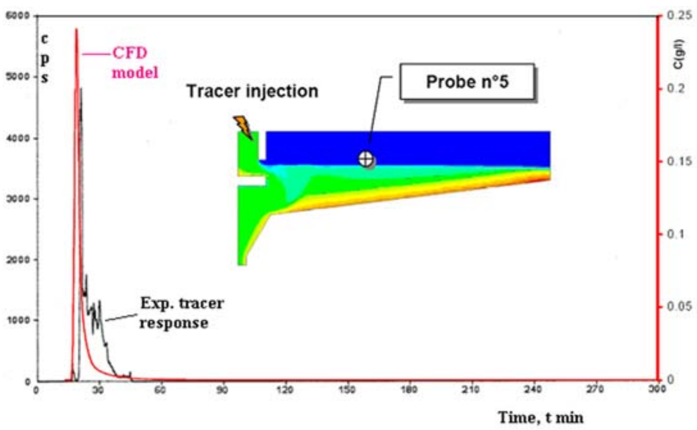


FIG.52. Comparison between CFD model and radiotracer experiment – Probe D5.

Results:

- Head and tail of the signal are well reproduced; numerical velocity field in the sludge blanket is close to the on-site velocity field,
- However, the signal is more dispersed within the experiment, which can be explained by the dispersion at the entrance ,
- Probes n°2-5-8 located in the middle of the process give the best agreement between experimental and numerical results.

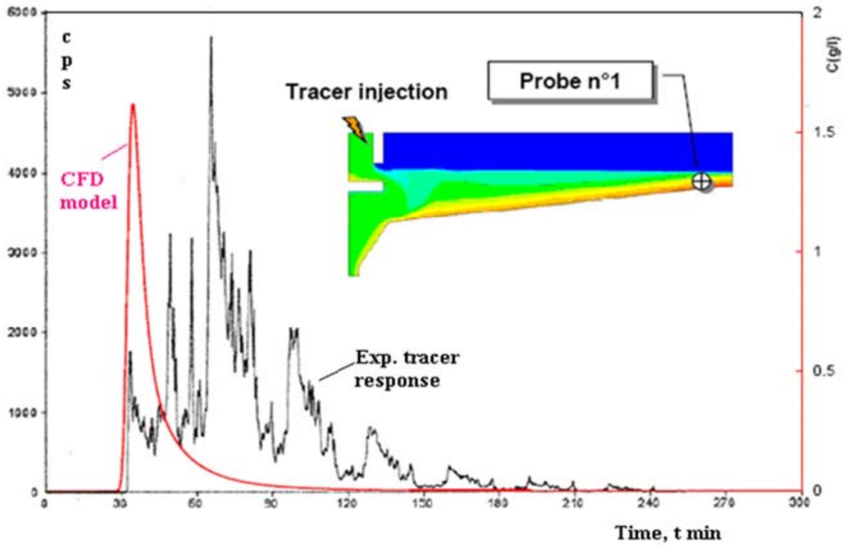


FIG.53. Comparison between CFD model and radiotracer experiment – Probe D1.

Results:

- Sludge in the bottom of the tank is of high concentration and possesses a longer residence time than in other region (between 120 and 150 minutes),
- Experimental results show heterogeneity in different angles and periodic pulsations in the signal of the tank which can not be reproduced by a 2D axial CFD simulation.

Conclusion

For tracer experiments:

- Short circuit is observed both for water and sludge: an important fraction (from 10 to 30 % of the flow) is transferred directly to the recirculation circuit without entering the clarifier.
- The repartition of water and sludge is very heterogeneous in the clarifier. Tracers are observed in all the system but with very high variations of concentration.
- Low quantities of labeled sludge are transferred to the outlet (less than 1% of the injected activities) showing the good efficiency of the clarifier.
- It has been possible to measure reliable radial velocities of sludge and water particles inside the clarifier for various functioning conditions.
- It has been possible to measure the mean residence time distribution of water and sludge inside the clarifier for various functioning conditions.

For the CFD model:

- Rheology modeling using CFD simulation is not reliable, in particular for solid phase and scraper flow motion,
- Comparison with tracer studies gives relatively good agreement in region where the scraper effect is negligible (clarified zone & middle probes).

4.8. DIAGNOSIS OF A CYLINDRICAL TWO-STAGE ANAEROBIC SLUDGE DIGESTER

(a) Introduction

The effective mixing volume of a cylindrical sludge digester was investigated using radiotracer method. Generally, after a long operation period, the effective mixing volume of a digester is gradually reduced increasing scaling of solid material in the stagnant (dead) zone. This solid sludge should be removed. The deterioration of the sludge flow is even more serious in a cylindrical 2-stage system (Fig. 54), which has only a gas bubbling mechanism in the primary digester and none in the secondary digester for the mixing.

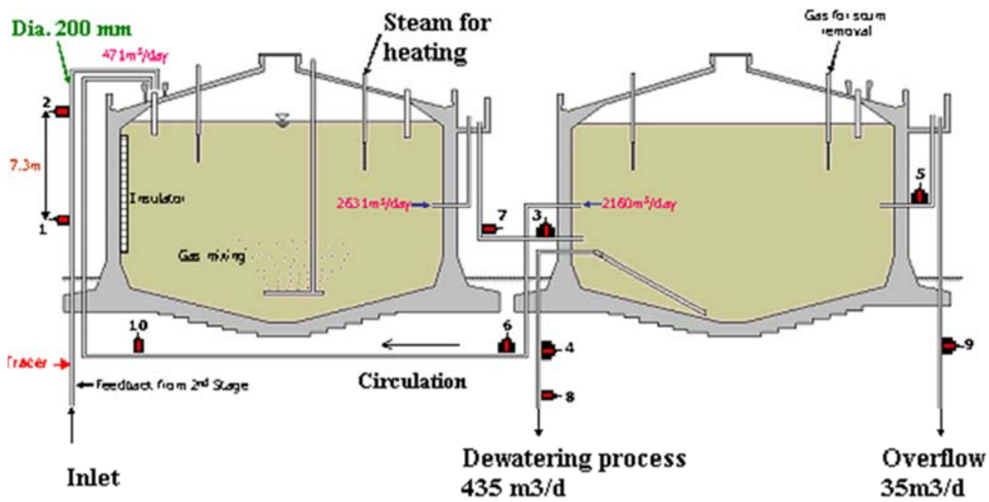


FIG.54. The diagram of the cylindrical 2-stage sludge digester.

A cylindrical two stage sludge digester was investigated for performance efficiency using radiotracer. Digesters have a capacity of 4980 m^3 each one. This digester system has been investigated by radiotracer experiment and considerable dead volume was found out. Right after the cleaning up another radiotracer experiment was carried out to quantitatively evaluate the improvement brought about by the cleaning work.

(b) Methodology

Taking account the size of digesters, its construction and medium, the selected radiotracer should have a relatively long life, high gamma energy and chemical stability in harsh operational conditions. Sc-46 was chosen as the optimal radiotracer in this case. Sc-46 can be produced in medium size nuclear reactor by the $^{45}Sc(n,\gamma)^{46}Sc$ reaction. After irradiation the Sc-46 was dissolved with EDTA creating a chemically stable tracer compound (^{46}Sc-EDTA). The radiotracer (50 mCi) solution was injected into the digester system by pressurized N_2 gas remotely operated.

Unlike the oval type digester made of steel, the concrete wall of the cylindrical digester was 1m thick, which only high energy gamma radiation can penetrate and reach the radiation probes installed outside of the digester. 2 inch NaI scintillation detectors were installed at inlets and outlets. The data acquisition system was used to collected detector signals continuously during 1 month period. The response functions of radiation probes were simulated with numerical model of continuously stirred tank reactor (CSTR) which was proposed by theoretical approach. The model parameters were used to compare the situations before and after cleaning work.

(c) Results

Flow rate measurement

The responses from the first two radiation probes after tracer injection were used for the flow rate measurement by the peak-to-peak method. The travel time of the tracer between the detectors was 7.46 seconds and the flow rate was calculated by the following equation where D is the distance between the detectors, 7.3 m and R is the internal radius of the pipeline, 0.1 m.

$$Q = \frac{\pi \times R^2 \times D}{7.46s} = 2{,}656 m^3 / day$$

RTD measurement

Over the period of the experiment the feed rate was kept constant at 471 m^3 and the recirculation was 2160 m^3.

The theoretical mean residence time was estimated at 1.89 days when it is assumed as a perfect mixer. In reality, however, the primary digester has only the gas bubbling mechanism for mixing the sludge and the secondary digester has nothing. In order to compare the flow patterns before and after the cleaning work, the RTD curves from each experiment were plotted in Fig. 55. The variance, the dispersion time distribution, has been greatly reduced after the cleaning and it means that the sludge flow has been activated more by using the volume of the digester more effectively. The break-through time and the maximum concentration time are increased as well after the cleaning.

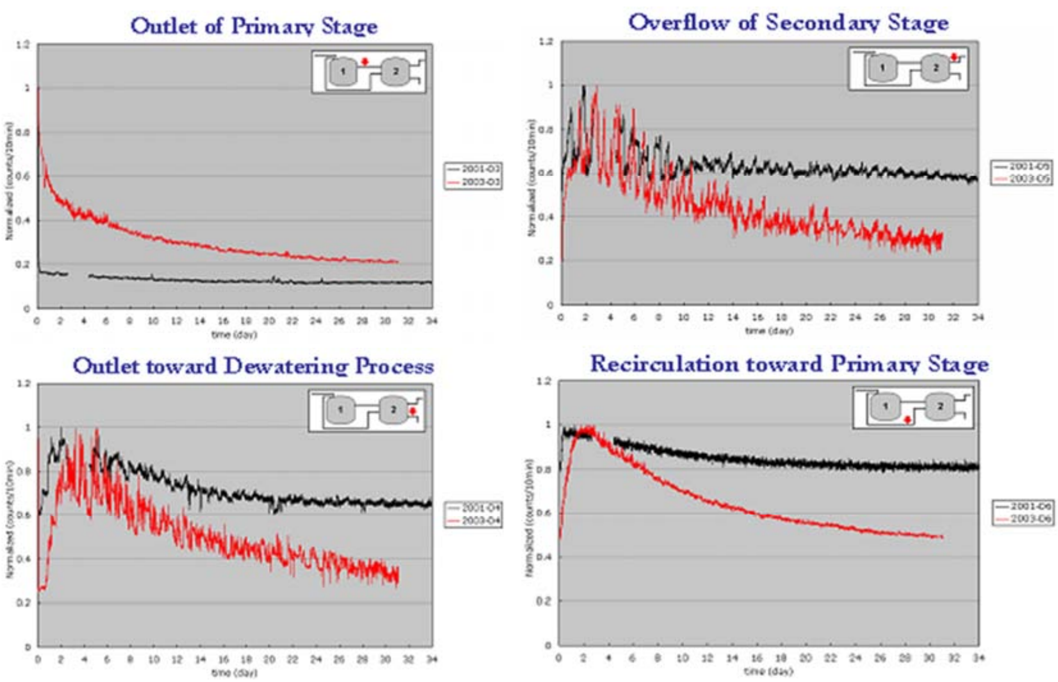


FIG.55. RTD comparison between before (black) and after(red) the clean-up.

RTD analysis by perfect mixer models

In Fig. 56 the simulated RTD curves from perfect mixers in a series with exchange volume are plotted along with the experimental results. As the feed rate and the circulation rate are controlled by mechanical pumping there is no difference in τ before and after the cleaning but the K-value, the ratio of the associated extra volume to the model volume has been increased by 2.5 times after cleaning. It can be concluded that the effective capacity for the sludge circulation including the secondary digester was only 40% of the current value. The mean residence time of the secondary digester has also been increased by 2.3 times after cleaning as shown in Fig. 57.

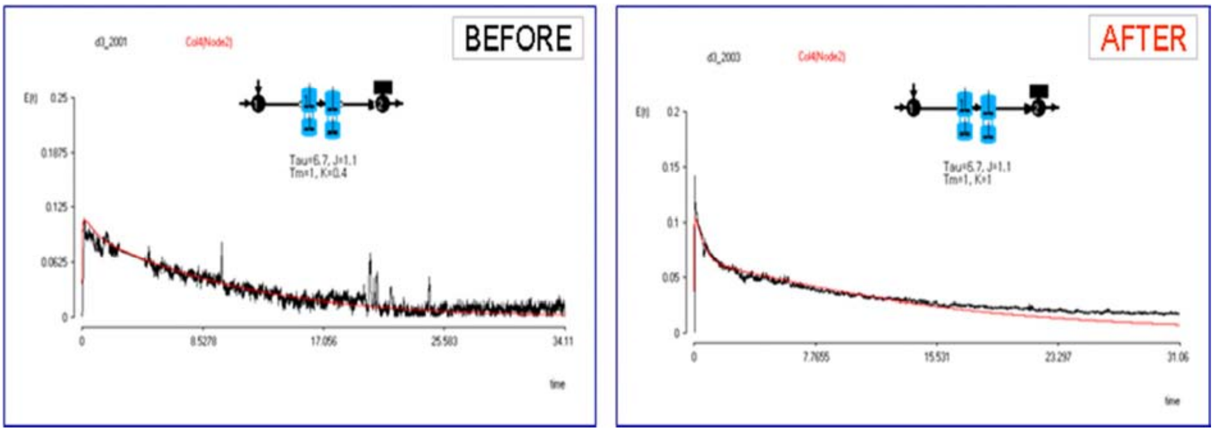


FIG.56. RTD simulation for experimental RTD profiles obtained at outlet of the primary digester.

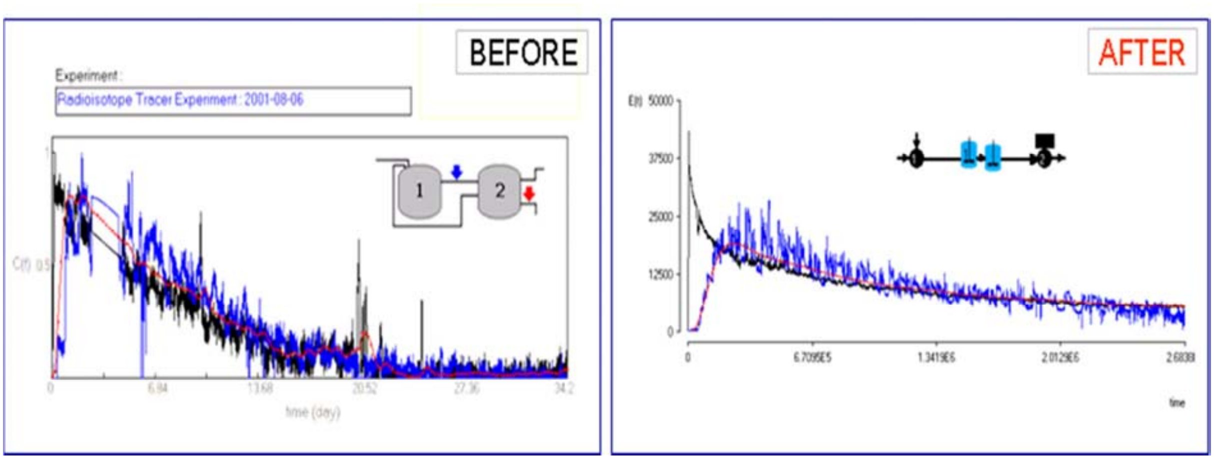


FIG.57. The results of RTD analysis on the secondary digester.

The digestion process was simulated with the perfect mixers in a series with exchange volume. The results are plotted in Fig. 57. In contrast to the small increase of the MRT of the primary digester, the MRT of the secondary digester has been remarkably increased (Table 7).

TABLE 7. COMPARISON OF MRTs BETWEEN BEFORE AND AFTER CLEANING-UP

Items		Before dredging		After dredging	
		primary	secondary	primary	secondary
MRT (day)	theoretical	1.95		1.89	
	experimental	1.37	0.4	1.6	1.6
Effective volume ratio		70%	20%	85%	85%

(d) Discussion of results

After the cleaning of the digesters the variance has been decreased and the sludge dynamics was activated as a result of the increase of the effective volume. Particularly the MRT of the secondary digester which has no mixing mechanism has been increased by 3 times. The dynamic behavior of the primary digester is strongly affected by the status of the secondary digester due to the circulation flow. Circulation improves the mixing effect without changing the mean residence time of the system.

The breakthrough time and the maximum concentration time at the outlet of the secondary digester have been greatly delayed, thus the sludge has more chance to be decomposed by the microorganisms in the digester than before.

Radiotracer study on cylindrical digesters revealed the change of the hydrodynamic characteristics after removing the stagnant zone. It is evident that results from radiotracer study can be used as a reference in the diagnosis of the efficiency of a digester system during its normal operation.

4.9. DIAGNOSIS OF OVAL SLUDGE DIGESTER

(a) Problem

Although some natural mixing occurs in an anaerobic digester because of rising sludge gas bubbles and the thermal convection currents caused by the addition of heat, these levels of mixing are not adequate to ensure stable digestion process performance at high loading rates. The long time operation of an anaerobic digester causes stagnant zone (or inactive volume), which reduces effective reaction volume and treatment efficiency. Therefore it is important to locate and quantify stagnant zone in digester for its optimal maintenance and effective operation. Poor quality of digested sludge is a common and often problem in practice.

Two oval sludge digesters in series were studied using radiotracer (Fig. 58). The scope of radiotracer tests was to assess the existence and location of the stagnant zone by estimating of mean residence time on the two stage anaerobic digester.

Radiotracer study on the digester can:

- Supply the information about the flow pattern of sludge without disturbance to the system.
- Enables to estimate the effective volume of digester
- Locate and quantify the stagnant zone inside digester.

FIG.58. View of typical oval(left) and cylindrical (right) sludge digesters.

(b) Radiotracer experiment

A radiotracer experiment was carried out on a two-stage anaerobic sludge digester with oval form. This system consists of a pair of digesters, primary and secondary digester. Each digester has a volume of 7000 m^3 respectively, and the flow-rate of the raw sludge in an inlet was 1500~1800 m^3/h. Sc-46 radioisotope (1.85 GBq) was chosen as radiotracer taking account the relatively long residence time of sludge inside the digester. $ScCl_3$ was irradiated in the nuclear reactor and dissolved with EDTA solution resulting in the ^{46}Sc-EDTA complex compound, which is a good tracer of water phase of the sludge.

The radiotracer was chosen to trace the water phase of the sludge. As known, water and fine solids of a pulp or sludge have the same behavior in most of reactors, thus the radiotracer compound used follows the sludge hydrodynamic behavior inside the digester system. Seventeen NaI 2” × 2” scintillation probes were installed around the digester walls to evaluate the flow behaviors inside the digester (Figs. 59 and 60). After the radiotracer instantaneous (Dirac) injection the radiation was measured every second during the first 10 minutes to record fast processes, and then measuring interval was kept 10 minutes. It took 33 days from the injection to collect the whole radiotracer signals.

(c) Discussion of results

The analysis of experimental results for the primary digester is shown in Fig. 61.

Figure 61 shows several experimental responses at various locations around the primary digester. D4 is the probe installed at the outlet of primary digester. Figure 61 b shows that the experimental RTD curve fits better with a perfect mixer and the MRT results 7.4 days. The primary digester as a whole behaves as a perfect mixer.

Similar results were obtained for probes D8 and D9 located at the upper part of the primary digester (Fig. 61, e &f). These detectors indicate that the digester zones in front of them are behaving as perfect mixers, with MRTs 7.5 and 7.1 days, respectively. Probe D3 located in front of the recirculation flow also indicates a perfect mixing zone in front of it (Fig. 61, a), with a MRT of 7 days. As shown above the parameters of flow dynamics provided by probes D3, D4, D8 and D9 are almost the same. However, detector D6 and D7 located on the lower part of a digester showed different flow patterns from those of probes in the upper part of digester (D8 and D9). Intensity of radiation detected by probes D6 and D7 was substantially lower than those of the detectors in the upper part of the primary digester. At the beginning (after radiotracer injection), D6 and D7 showed no radiation indication, and later on tracer appeared reaching a peak. After the peak, the curves decreased exponentially with time having a long tail, which indicates the presence of stagnant zones in these parts of the digester. Because of the stagnant zones, the MRTs of sludge in zones in front of probes D6 and D7 were found, of 10.2 and 15.2 days, respectively (higher than the theoretical MRT of the primary digester).

The probe D5 placed at the bottom part of the digester did not show any tracer signal at all during the experiment duration. This indicates the presence of a sludge scale layer in this part of digester (7~9 m above the ground level from the bottom). Using the signal of the detector D4 as an inflow a similar analysis was carried out for the secondary digester.

The results of the secondary digester are shown in Fig. 62.

The secondary digester has no mixing facility and functions only to separate the mixed sludge being delivered from the primary digester statically.

Detector D11 installed at the bottom part of the secondary digester did not show any tracer indication during the experiment time (similar result with detector D5 in primary digester). Detector D16 installed at the outlet of the secondary digester gave a MRT of 6.3 days (Fig. 62, b), which is lower than the theoretical MRT of 8.5 days calculated for the secondary digester. The detector D12 showed relatively low radiation counts and a long tail, giving a MRT of 11.2 days. This is apparently caused by stagnant zone in front of this detector.

The total MRT calculated between the inflow of the primary digester and the outflow of the secondary digester (D1-D16) was 13.5 days (Fig. 62, c). Compared with the added result of MRT (D1-D4) + MRT (D4 - D16) = 7.4 d+ 6.3 d = 13.7 days, it results almost the same. This confirms the correctness of the calculations.

The results of the radiotracer test on the anaerobic digester are summarized in Table VIII.

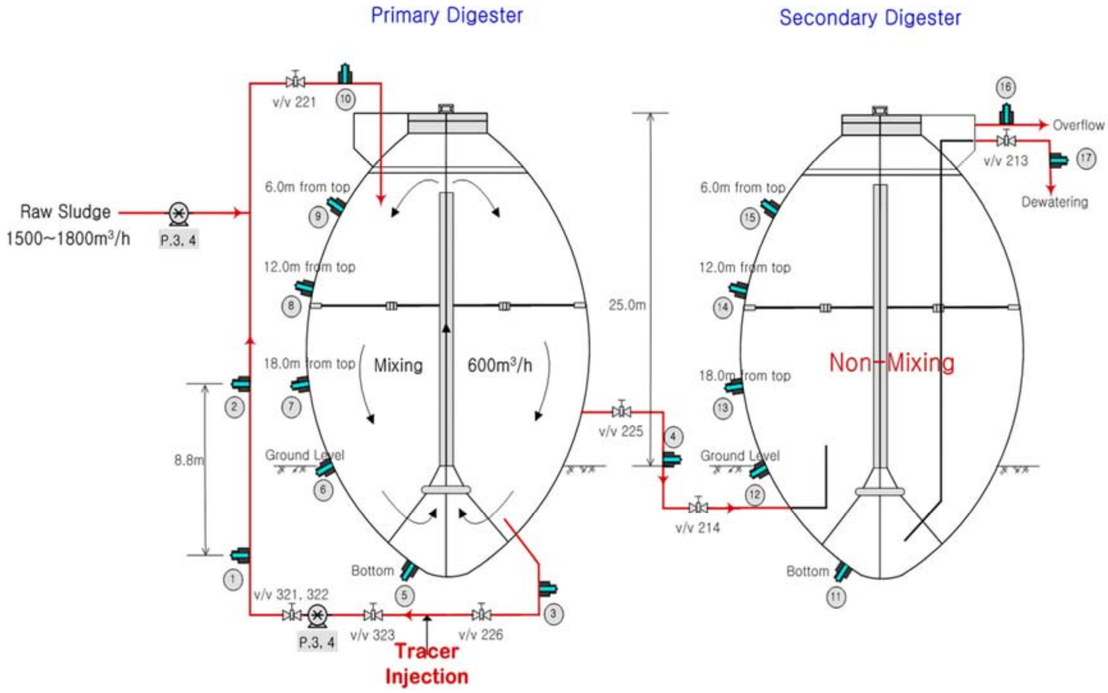
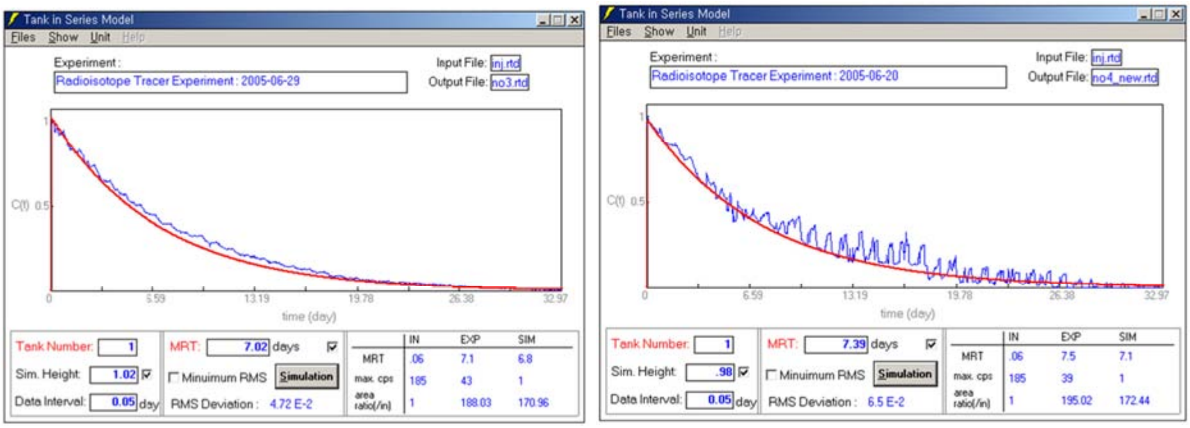
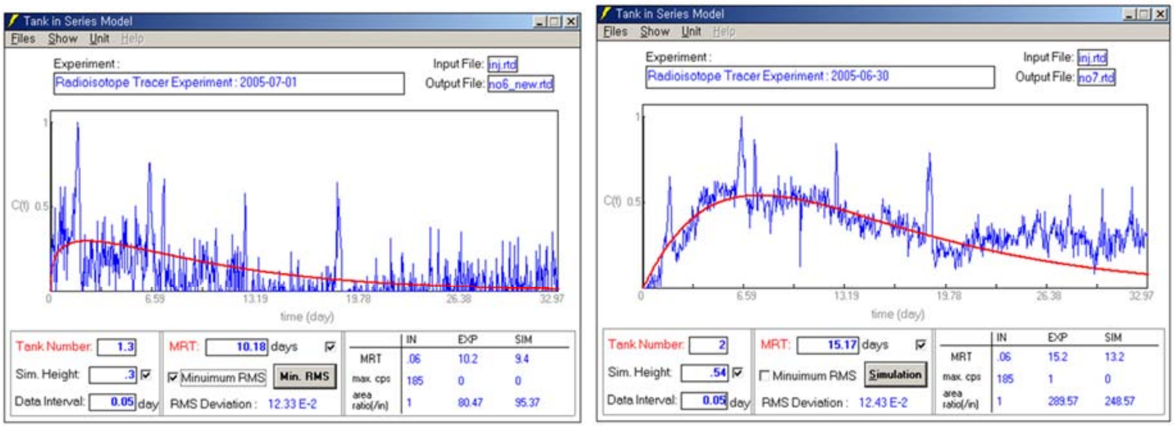


FIG.59. Radiotracer experimental design: position of detectors.

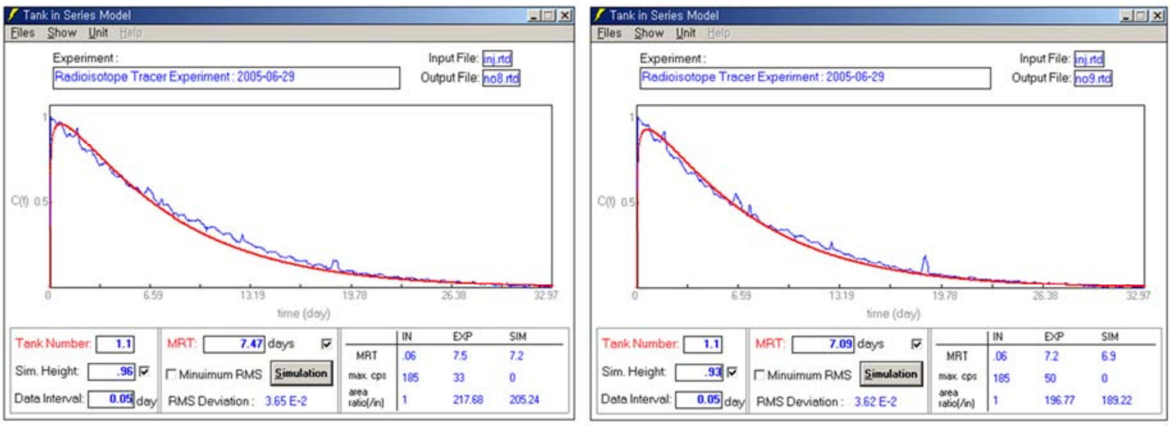
FIG.60. Some NaI detectors installed around digester.



(a) D1 - D3 (b) D1 - D4

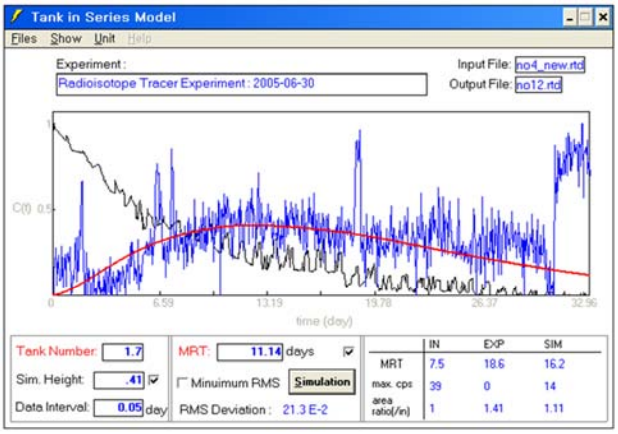


(c) D1 - D6 (d) D1 - D7

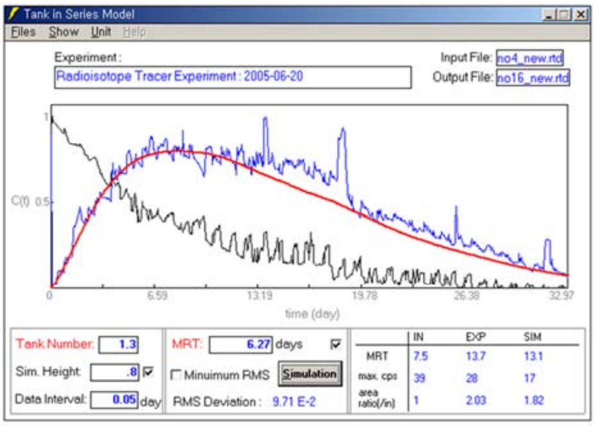


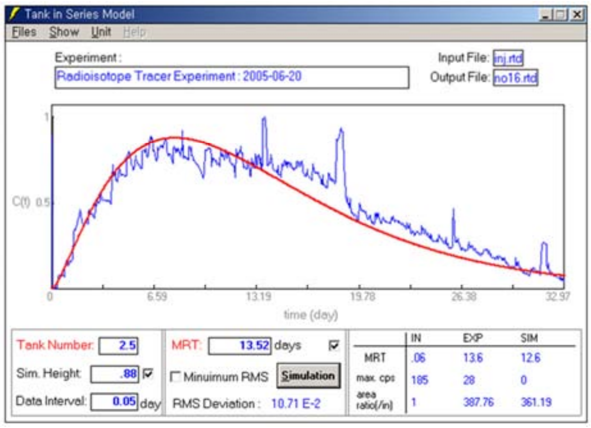
(e) D1 - D8 (f) D1 - D9

FIG.61. RTD analysis of the primary digester with perfect mixers in series model.



(a) D4 - D12





(b) D4 - D16 (c) D1 - D16

FIG.62. RTD analysis of the secondary digester.

TABLE 8. RTD RESULTS OF THE TWO STAGE ANAEROBIC DIGESTER

Digester	Detector No.		Tank number	MRT (theory)	MRT (measured)	Active volume	Dead Volume
Primary Digester	In	D1	1.0	8.5d	7.4d	87%	13%
	Out	D4					
Secondary Digester	In	D4	1.3	8.5d	6.3d	74%	26%
	Out	D16					
Total	In	D1	2.5	17.0d	13.5d	79%	21%
	Out	D16					

The dead volume was estimated by using the following equation:

$$DV(\%) = \left(1 - \frac{MRT_{exp}}{MRT_{th}}\right) \times 100$$

where DV means the percentage of the dead volume to the total volume. MRT_{exp} and MRT_{th} are the experimental MRT and the theoretical MRT, respectively.

(d) Conclusions

The diagnosis of digester system was performed by applying radiotracer test. The existence of stagnant zones in the two stage anaerobic digester quantified and located. The primary digester has an active zone of 87% and a stagnant zone of 13%, while the secondary digester has 74% active zone and 26% stagnant zone. Experience has shown that under normal operation the anaerobic digesters have an acceptable stagnant zone up to 20-30 % that means the tested anaerobic digester system needs no cleaning work at this moment. The stagnant zones were observed at the lower part of the digester, mostly located at the bottoms of the digesters.

Based on these conclusions the constructed location of the dead zones inside the digester system is shown in Fig. 63.

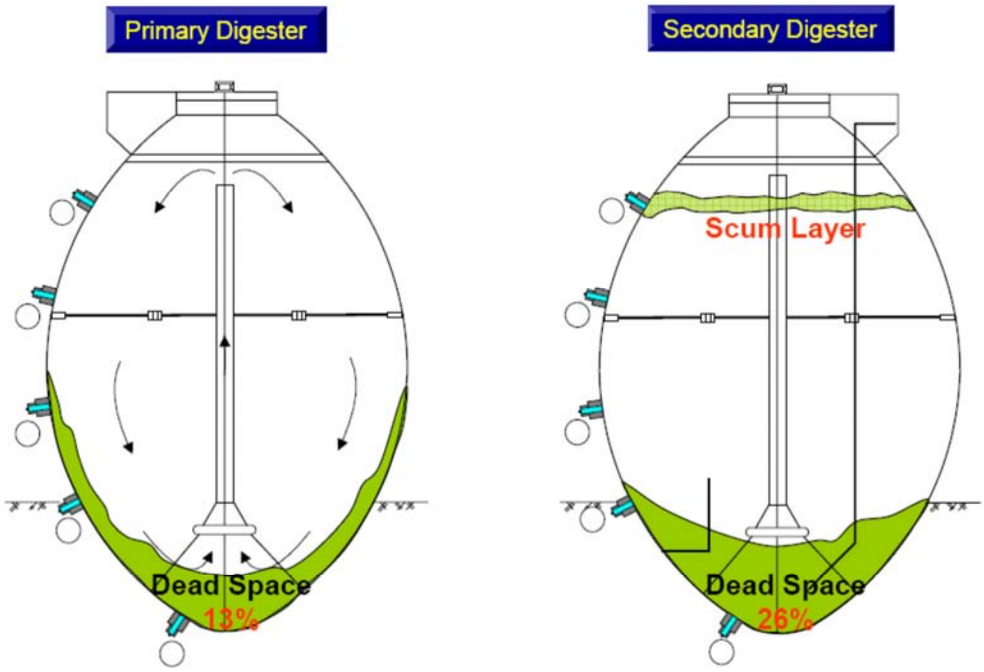


FIG.63. The constructed location of stagnant zones in the digester system.

4.10. RADIOTRACER INVESTIGATION OF AN ANAEROBIC DIGESTER

(a) Problem

The WWTP engineers wanted to investigate the operation of anaerobic digesters and better know the behavior of mud (< 40-60 µm) and sand (125 - 163 µm) in this installation. It was a question in particular of better determining the rate of clogging of a digester what is important in term of maintenance of the installation. Such a study requires the knowledge of the transfer functions of mud and sand in the digester and, in particular, their temporal characteristics. The methodology of the radioactive tracing is particularly adapted to meet this aim because of:

- the specificity of the traced particles (either mud or sand exclusively),
- the sensitivity of the measurements,
- the no intrusive character of the method which allows an in situ detection.

To determine the temporal parameters of mud and sand flow, two tracing tests were carried out:

- mud tracing,
- sand (125-163 µm) tracing.

(b) Digester design

Figure 64 presents the simplified design of the digester. The digester has the following characteristics:

- volume : 7000 m^3
- internal diameter : 25.6 m
- high : 15.3 m
- digester gas flow rate (1 m^3 biogaz.m^{-2}.d^{-1})
- flow rates: 160 m^3/d for mud and 135 m^3/d for sand.

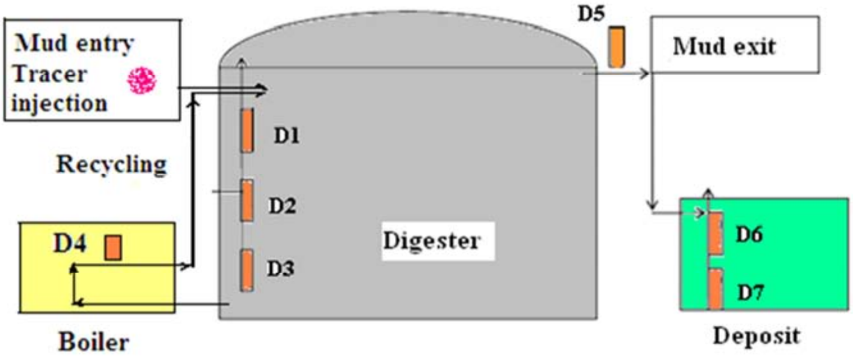


FIG.64. Schematic view of digester and location of detection points.

(c) Tracer injection and detection

The tracer was injected into the main charge tube of the digester near the boiler. The tracer detection points (Fig. 64) were selected according to the access possibilities. It should be noted that the possibilities of access to the digester are very limited and that it was not possible, because of constraints of exploitation, to consider any modification with the existing system. Thus location of the detectors was not optimal.

The position of the radiation detectors were as follows:

- D1: under the cover of entry, depth 4.25 m
- D2: under the cover of entry, depth 7.50 m
- D3: under the cover of entry, depth 11.65 m
- D4: external circuit of recirculation
- D5: in the mud exit, depth approximately 2 m
- D6: in top of storage
- D7: in bottom of the storage.

The signals relating to the detectors D4, D6 and D7 were not exploited here for the following reasons:

- detector D4 was positioned on a branch off-line of the line of recirculation, no signal could thus be measured by this detector
- detectors D6 and D7 were positioned in front of the storage, which particular hydrodynamics masks that specific to the digester.

(d) Mud tracer

Mud tracer was Hafnium – (175-181), which was selected because of its proper characteristics for this investigation:

- half life: 45 days (effective half life of both radioisotopes Hf-175 and Hf-181 that are generated during radiation of natural isotopes of hafnium in the nuclear reactor),

- average gamma energy of 400 keV. which makes it easy operational for the used activity of 70 mCi (2.6 GBq),
- can be fixed easy and strongly on mud particles,
- 500 mg Hafnium are used for labeling of 1 kg dry mud, thus the labeling does not modify the hydrodynamic behavior of mud particles.

(e) Labeling of sand particles of 125 - 163 μm

Sand was imitated with glass particles of the same granulometry. Isotope of Iridium-191, which is easy activable in the nuclear reactor to produce radioisotope Iridium-192, was introduce in the glass preparation. Iridium -192 was selected because of its proper characteristics:

- half life: 74 days,
- gamma energy of ≈ 400 keV, which is easy operational for used activity of 100 mCi (3.7 GBq),
- mass of radioactive sand (glass) injected into the digester was 240 g.

(f) Data treatment and interpretation

The radiation detectors employed were NaI(Tl) (1,5” × 1”) connected to a data acquisition system. The measurements were performed online every 15 minutes. The data were corrected for radioactive decay and background. The first attempt was to estimate the mass balance. Assuming the flow rate Q constant, the curve areas can be used to find the mass balance. The response curve area S is proportional with the activity A and inverse proportional with the flow rate Q:

$$S = k \times (A/Q)$$

where: k is a constant which depends on tracer energy, tracing medium and the detection geometry.

In fact there was not condition to apply for mass balance because the mediums and local flow rates in front of detectors D1, D2, D3 and D5 were not the same. The most reliable information can be obtained from the residence time distribution (RTD) functions only.

(g) Mud dynamics

The experimental RTD curves for detectors D1 and D2 are shown in Fig. 65. These curves have been normalized on the surface because they return well ‘to zero’. The normalizing makes it possible to be freed from the effects of calibration which can vary according to detectors' and to express the signals in the form of reduced concentration.

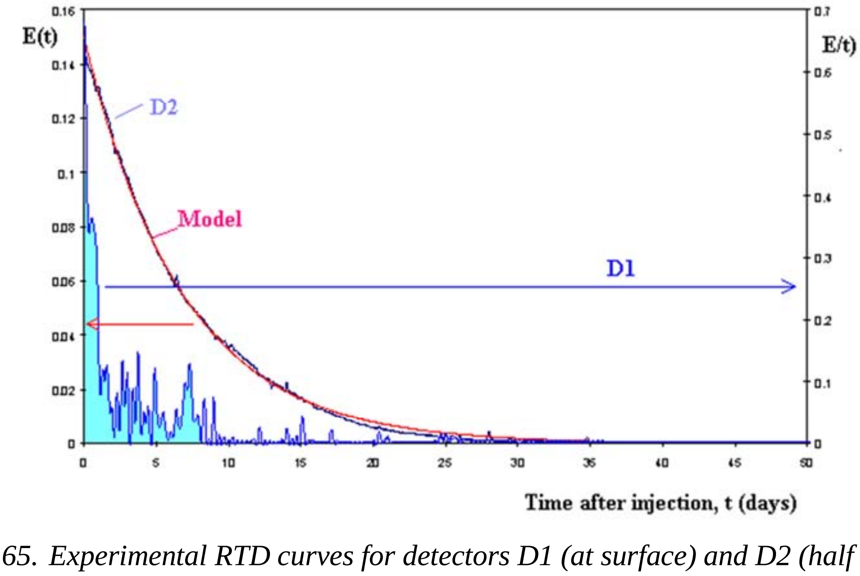


FIG.65. Experimental RTD curves for detectors D1 (at surface) and D2 (half depth).

The examination of Fig. 65 shows that the signal relating to detector 1 ‘falls’ very quickly at the end of a day approximately while that relating to detector D_2 is very correctly adjusted by exponential decreasing of time-constant equal to 6.8 days.

These observations make it possible to estimate that the tracer probably does not have time to mix radially in the top of the digester but which it has rather tendency ‘to fall’ towards the bottom. An explanation could lie in the fact that the tracer was ‘taken’ in a particular mud cluster. At half height however, the tracer can be considered as good mixed in the vicinity of the volume of detection of detector D_2.

The experimental RTD curve obtained near the bottom of the digester by the detector D_3 and its model are shown in Fig. 66. It was not normalized because it was not closed to zero (it is expressed in counts per seconds, cps). The mean residence time of this curve was found of 32.6 days. In the same Fig. 66 is plotted for comparison the RTD obtained by detector D_2. The green curve shows the difference between two curves, that means represents the maximal quantity of mud that falls down and deposits somewhere at the bottom of digester. It represents 80% of mud flow rate circulating at the digester bottom.

The experimental RTD curve obtained from detector D5 (mud exit) is given in Fig. 67. It indicates that the digester behaviors like an ‘axial dispersion plug flow’ than a perfect mixer.

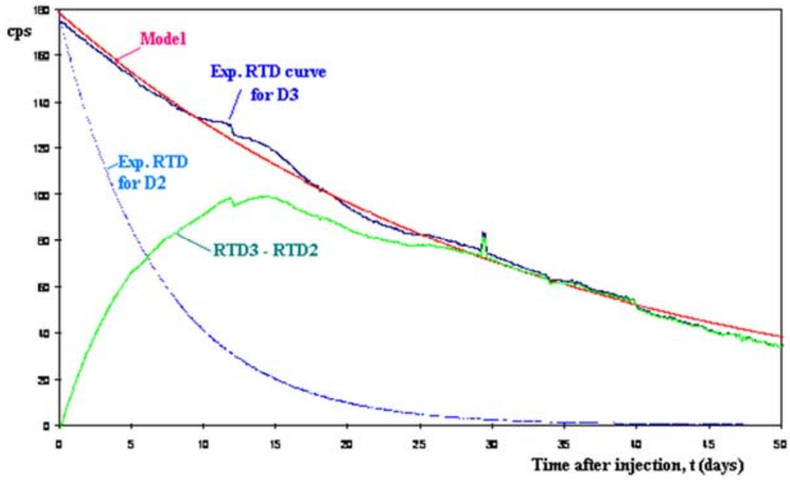


FIG.66. Experimental response for detector D_3 (digester bottom) an dits model.

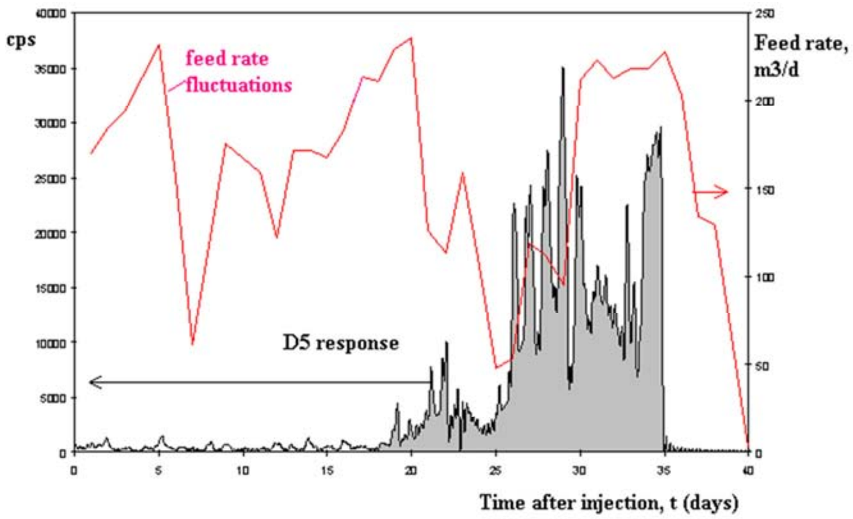


FIG.67. Experimental response of D5 (mud exit) and feed rate fluctuations.

To estimate the MRT of the mud inside the digester the correction for flow rate fluctuations has to be performed. As seen from the Fig. 67 the flow rate fluctuated during the tracer test duration (red line). It exists the relation:

$$E_m = E(t)\ [Q(t)/Q_m],$$

where Q_m is the average flow rate, Q(t) is the flow rate of the day when the signal E(t) was obtained.

It was calculated the average MRT of the mud inside the digester of 31 days, which gives an active volume of 5000 m^3. The dead (stagnant) volume resulted 7000 – 5000 = 2000 m^3 or 30% of total volume of digester. This dead volume may be caused either by deposition of mud on the digester bottom or by presence of sides where flow is practically not entering.

The analysis of experimental RTD curves obtained by detectors D_1, D_2 and D_3 indicates that the digester behaviors like a mixer crossed by different flow rates. Taking into account the tracer data and the digester design, a model was proposed for the circulation of mud inside the digester (Fig. 68).

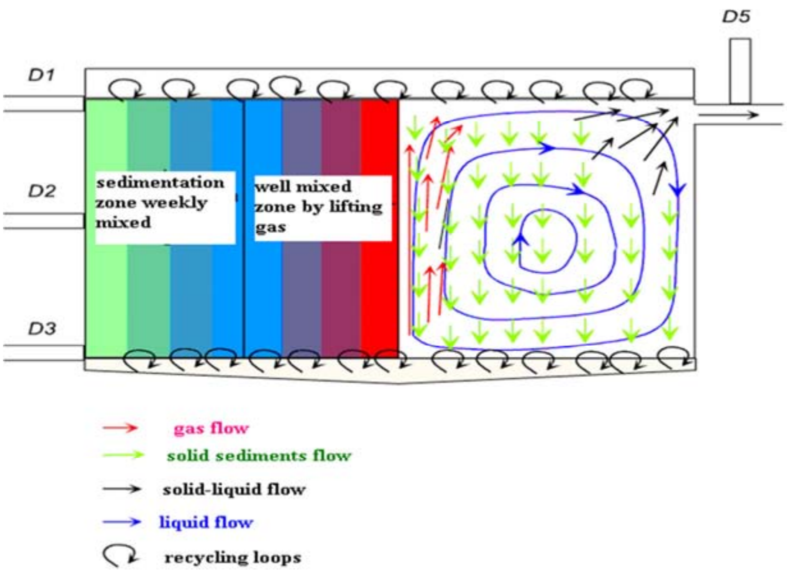


FIG.68. Possible model of mud movement inside the digester.

The lifting gas moves the liquid and the turbulence generated by the gas flow diminishes from the digester center towards its walls. Liquid flow moves the sediments and the gas bubbling helps the mud mixing. Liquid movement and lifting gas can keep in suspension the mud on the digester bottom as well. At the end, aspiration of mud towards the mixer exit may be disturbed from different circulating flows. This hydrodynamic behavior is responsible for the tracer dispersion at the exit of digester.

(h) Sand dynamics

Figure 69 shows the experimental RTD curves obtained for sand tracer by detectors D1, D2 and D3.

The examination of this figure indicates that the experimental RTD curves relating to detectors D1 and D3 (surface and bottom of the digester) are practically identical, while that relating to the D2 detector presents an extremely different behavior with a more agitated dynamics.

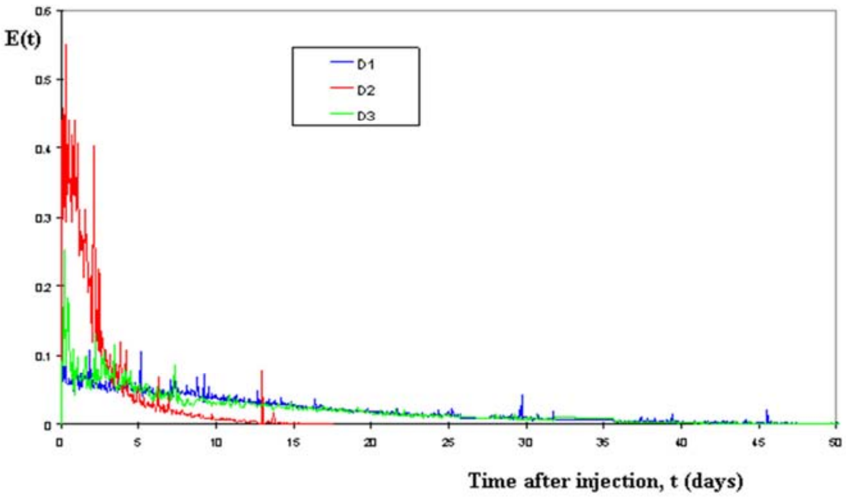


FIG.69. Experimental responses of detectors D1, D2 and D3 for sand tracer.

With intermediate scale (of the order of twenty days), the examination of the three preceding signals highlights rather regular structural oscillations which diminish in the course of time, whatever the position of the detector in the digester. A systemic approach of these flows breaks them up into two principal types; one corresponding to a well mixed main flow, the other to secondary flow consisted of local recirculations. A model based on this concept is illustrated by Fig. 70 and is correctly validated as proven in the Figs. 71, 72 and 73.

In order to compare with the flows suggested on the left part of Fig. 68, the principal branch of the systemic model contains one mixer only, which describes the slightly mixed, mainly sedimentary zone. The secondary branch contains an arrangement of reactors in recirculation, which describes the central zone mixed well by the gas spin; the downward branch is representing the liquid flow while that ‘recycling’ could be representative of the gas flow. This modeling seems to indicate that 90% of the material falls towards the bottom of the digester.

Practically, the behavior of traced sand is comparable with that of tracer mud even if the corresponding signals do not have the same oscillations. The internal dynamics of both sand and mud is the resultant of the competition between sedimentation and the tendency to the homogenization (strong on surface and the bottom, weak with semi-depth) in the digester.

An estimate of the maximum sand flow accumulating at the bottom leads to 70% of the sand flow traversing the bottom of the digester to be compared with the 80% estimated at the time of the tracing of mud. It is very probable that the difference, on the assumption that it is significant, is due to easier reentry of mud towards the exit of the digester.

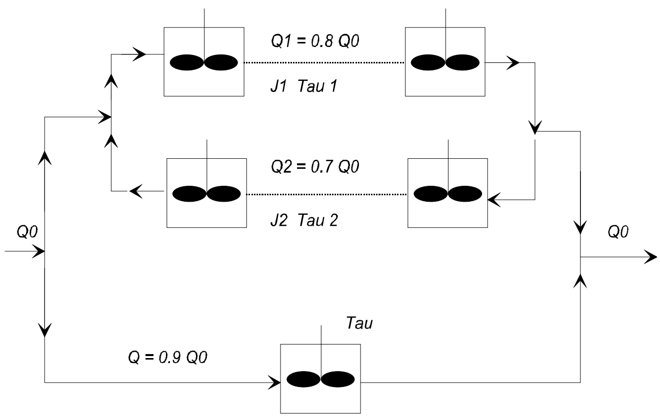


FIG.70. Supposed global model of mass flow in digester.

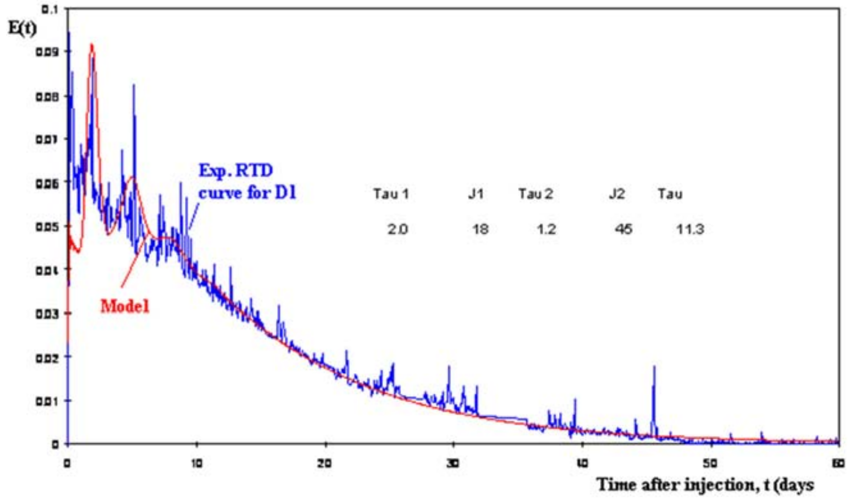


FIG.71. Experimental RTD curve and its model for D1.

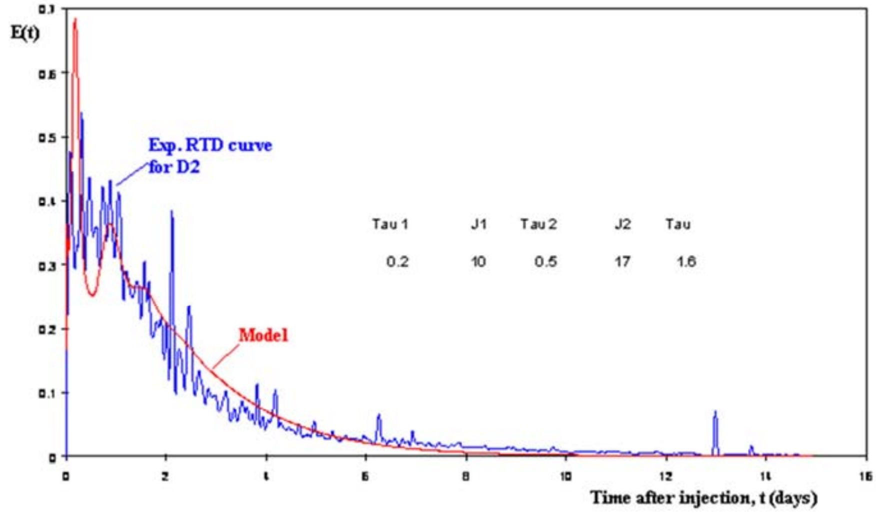


FIG.72. Experimental RTD curve and its model for D2.

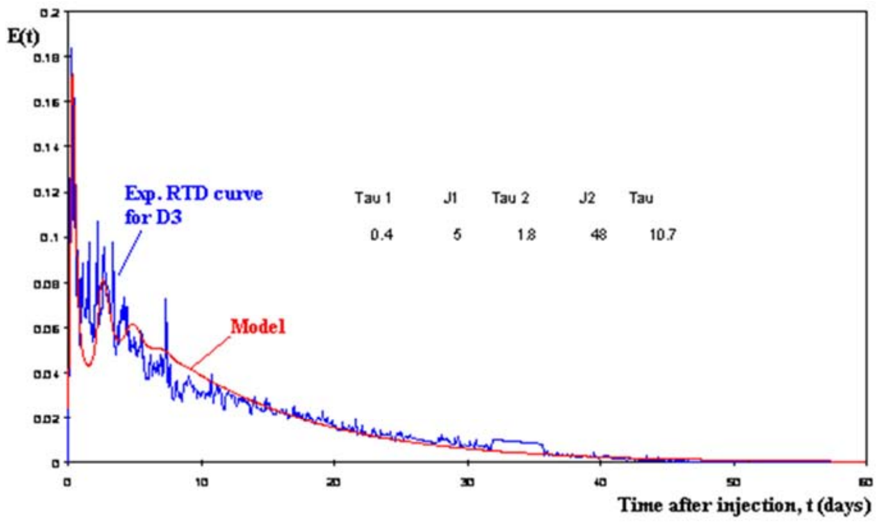


FIG.73. Experimental RTD curve and its model for D3.

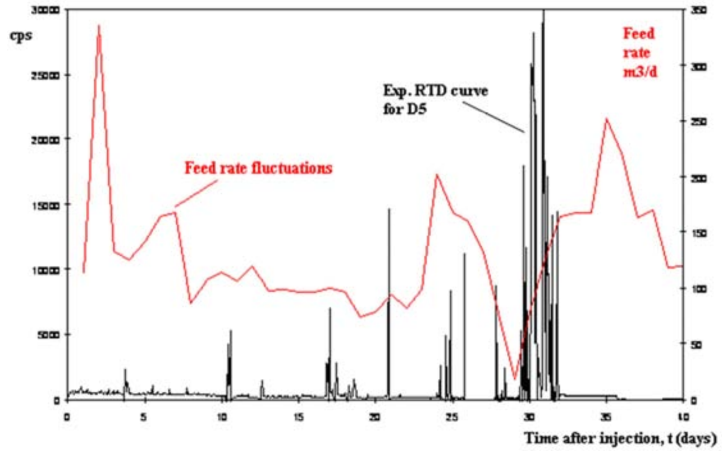


FIG.74. Experimental RTD curve for D5 (sand exit) and fluctuation of feed rates.

Lastly, the experimental mean residence time's of the sand was calculated taking account the feed rate fluctuations as was done in the case of mud tracing. Fig. 74 provides the experimental RTD of sand measured at the digester exit (D5). This shows that the digester cannot be modeled as a whole with a perfect mixer. An estimate of the MRT of sand in the digester gave the same value of about 31 days. Taking into account the average sand flow rate of 135 m^3/d and the physical volume of digester of 700 m^3, it results that 40% of the total volume of the digester is thus not traversed by sand; this dead volume can be related on the clogging of the digester but also on the presence of zones difficult to reach to the sand flow.

(f) Conclusions

Mud and sand tracing provided the hydrodynamic behaviors of solid phase inside the anaerobic sludge digester. A possible dynamic model was proposed. The internal behavior of sand and mud showed a competition between the tendencies to sedimentation and homogenization. The latter is favored on the surface probably because of the possible bubbling related to degasification. At the mid-depth, sedimentation seems favored, whereas towards the bottom the tendency to homogenization seems to prevail again. This tendency could be due to the presence of loops of recirculation generated by various liquid and gas flows. Estimates based on the mean residence times of mud and sand lead to important values of the dead (or stagnant) of about 30 to 40% of the total volume of the digester. A tracing of gas phase could verify some of the assumptions put forth at the time of this study. Lastly, the confrontation of these results with modeling by computer fluid dynamics (CFD) simulation of the multiphase flow (gaz/liquide/solide) would be interesting for the near future.

4.11. RADIOTRACER INVESTIGATION OF MUNICIPAL BIOLOGICAL AERATION TANK

4.11.1. Problem

The design of the biological aeration tank investigated using radiotracer technique is shown in Fig. 75. It has a volume of 3000 m^3. The main goal of the radiotracer test was to verify whether there occurs any short circuit flow from the inlet to the outlet of the tank.

4.11.2. Radiotracer test

The radiotracer used for water phase was Br-82 as $NH_4{}^{82}Br$ (1000 MBq/injection). Tracer solution (500 mL) was pumped as an instantaneous injection down to label wastewater in the submerged inlet to the tank. Figure 76 shows the injection system and the radiotracer mobile lab (inside the truck).

Three detection probes were employed. Two probes (D1 and D2) were immerged inside the aeration tank for detection of inlet intrusion into the assumed clockwise rotating water body (Fig. 76). A third probe (D_3) was placed in a flow through detection chamber from the tank outlet (Fig. 77). Probe D_3 monitored the discharged effluent.

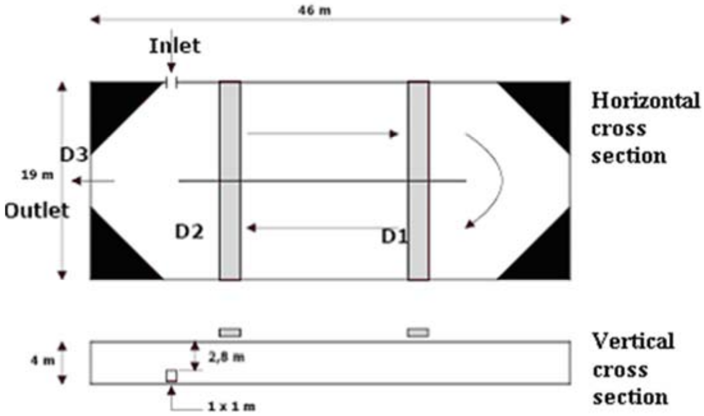


FIG.75. Biological aeration tank.

FIG.76. Mobil tracer lab and tracer bottle for injection.

FIG.77. Location of probes: D_2 immerged and D_3 inside detection chamber.

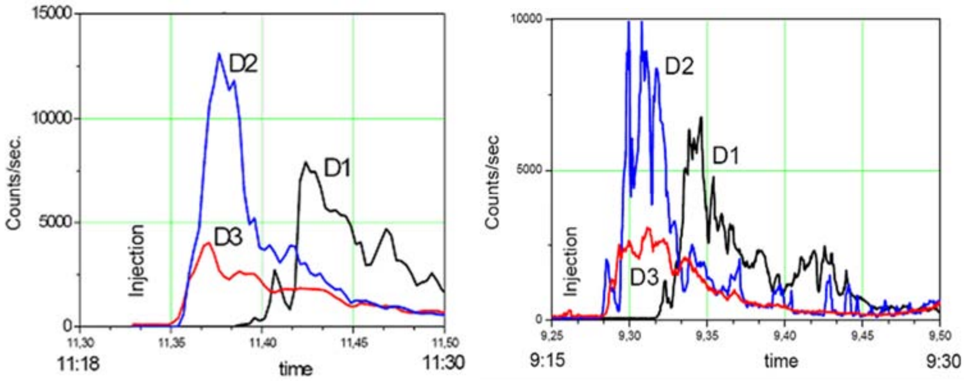


FIG.78. Experimental RTD curves in two tests.

The tracer movement for a normal assumed flow regime should go from the inlet to the probe D_1, after to the probe D_2 and at the end to the probe D_3. Fig. 78 shows that the response signal recorded by detector D_3 comes before the signal recorded by detector D_1. This indicates that a significant part of the wastewater flow is bypassing directly from the inlet to the outlet. The flow regime in this aeration tank was found abnormal and modification of the inlet position and installation of baffles were recommended to improve the efficiency of this WWTP's unit.

4.12. ^{99M}TC AS A TRACER FOR THE LIQUID RESIDENCE TIME DISTRIBUTION MESUREMENT IN ANAEROBIC DIGESTER: APPLICATION IN A SUGAR WASTEWATER TREATMENT PLANT

4.12.1. Background

Different chemical and radioactive tracers have been employed for diagnosing the hydrodynamic of anaerobic processes: $K^{82}Br$, HTO, $K^{131}I$, rhodamine-WT and lithium chloride to trace wastewater, and ^{113m}In ($InCl_3$), ^{140}La and ^{198}Au for the sludge. However, for the countries which do not have nuclear reactor facilities for the production of such radioisotopes, the only possibility to extend the application of radiotracer techniques in sanitary engineering is the employment of radioisotope generators.

Among the commercial radioisotope generators the $^{99}Mo/^{99m}Tc$ generator, due its generalization in nuclear medicine for the production of labeled compounds, seems to be an attractive approach. However, the use of this tracer in anaerobic process must be preceded by the study of the physico-chemical behavior of the eluate: the pertechnectate ion ($^{99m}TcO_4^-$).

The validation of ^{99m}Tc-pertechnetate as radiotracer to measure the RTD of the liquid phase in anaerobic digester has to be done. For this purpose, a new digester developed by the Cuban Research Institute of Sugar for the treatment of the effluent of the sugar factory has been selected. The anaerobic digestion processes need physico-chemical conditions easy to work: temperature around 30°C, pH between 6.8 and 7.8, absolute anaerobic medium, volatile fatty acids concentration around 1 $g \cdot L^{-1}$.

Previous investigations have shown that the lithium tracer was adsorbed slightly onto the packing medium and held up within the biomass. Similar observation has been made for rhodamine dye diffused into the biofilm during the influx of tracer, and out-diffused slowly. The consequences were as much as 100% error in retention time. Therefore, when attempting to model reactor hydraulics, extreme care must be exercised in the choice of tracer compound and in the ultimate interpretation of RTD functions obtained.

4.12.2. Radiotracer experiment

(a) Laboratory batch sorption experiments

For the sorption experiments, three representative wastewater samples were selected at different stages of the digestion process at the anaerobic digestion unit of the WWTP of the sugar factory based on a two phase's anaerobic digestion employing three hybrid reactors.

The main advantages of this technology are, the reduction up to 90% of the effluent pollution charge, the production of biogas and the attain of sludge that constitutes an excellent fertilizer. Nevertheless, in order to generalize and widespread this technology to other sugar factory, first of all, designs and process modeling must optimize plant operation.

Figure 79 gives the scheme of an industrial unit.

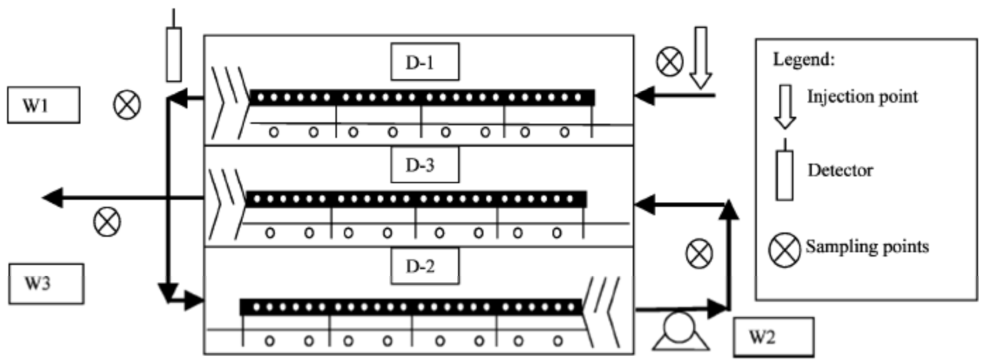


FIG.79. Scheme of the industrial unit.

W1 corresponds to the effluent that entry the unit; W2, the fluid circulating trough digester D_2 and W3 the fluid that exit the unit. The flow is pumping from D2 to D3 whereas it is going by gravity from D_1 to D_3 and from D_2 to the outlet (Fig.79).

A modification of batch experiment was used to evaluate the possible sorption of $^{99m}TcO_4^-$. The first step of the experiment was the pre-heated of wastewaters to ~37°C and the equilibration to the conditions founded during anaerobic digestion. For each sorption experiment, 200 mL of the wastewaters and 1 mL of the stock $^{99m}TcO_4^-$ solution (42,3 MBq/mL) were filled into polyethylene bottles. Another bottle filled with 200 mL of distilled water and 1 mL of $^{99m}TcO_4^-$ was used as blank.

Bottles were hermetically sealed by tightly fitting stoppers and shake up at ~150 oscillations per minute. After certain periods of time (1, 2, 4, 8, 16, 24 and 48 hours) the wastewaters were centrifuged during 10 minutes and filtrated through membrane filters of 0.45 μm pore size (Millipore). Three independent experiments were carried out with each wastewater and for each time and one further experiment with the blank to check for wall adsorption. 1 mL of filtering solution was withdrawn for radioactive counting (<5% relative error) using a NaI(Tl) well-type detector. Furthermore, pH and Eh of the solution were measured. The percents of Tc sorbed *U(%)* were calculated through the expression:

$$U(\%) = \frac{I_o - I_L}{I_o} \, x \, 100$$

I_o is the counting rate of the blank and I_L is the counting rate at the end of the experiment, in cps. The registered activity was corrected for ^{99m}Tc decay. From three independent measurements the mean percent of Tc sorbed was calculated. The relative error of *U(%)* may be high if the difference $I_o – I_L$ or the counting rate I_L are small.

(b) Full-scale plant tracer experiment

Tracer experiment was carried out for the normal operation flow rate of the plant (Q =14.4m^3/s). A pulse of about 37 GBq of sodium ^{99m}Tc-pertechnectate, first elution of a ^{99}Mo/^{99m}Tc generator was injected at the inlet of D_1. The activities were monitored with three shielded 1” × 1” NaI(Tl) detectors attached to the outlet of the first digester, and registered at digital ratemeters (Minekin). At the end of the experiment the data were transferred to a personal computer. Additionally, temperature and pH of the effluent at the outlet of the unit were systematically controlled, to check for gradient variations across the unit.

4.12.3. Results and discusion

It is very important to point out, that nevertheless that the mechanism of the observed sorption leads to a non-reversible loss of the tracer, this fact does not imply its delay in the system. This means that it is possible to employ this tracer in processes that does not require the quantitative evaluation of a certain parameters. In other words, ^{99m}Tc-pertechnetate can be employed for example, for the analysis of RTD functions in digestion process, as it has been proposed in the present work, for the determination of such parameters as the HRT, Peclet number, number of tanks, etc., but it is not recommended for determination of volumetric flow rate or flow across the system if exact value of these magnitude are required.

Previous to modeling, the experimental RTD curves were corrected for ^{99m}Tc decay, baseline was subtracted taking in account the quantity of Tc sorbed (according kinetic sorption studies performed early at Lab. scale) and finally they were normalized by area.

(a) RTD analysis and model parameter estimation

The experimental RTD data were treated for background subtraction and for ^{99m}Tc decay. The experimental RTD curve was normalized before the optimization of the parameters. Figure 80 shows the experimental RTD curve and its model. For the simulation of such complex systems the software DTS PRO V.4.2 was employed (Fig. 81). It allows the construction of any complex network of elementary reactors (such as plug flow reactor, perfect mixing cells in series, etc) properly interconnected to optimize the parameters of the experimental curve (Fig. 82).

A re-circulation of the sludge is assumed through many diffusers dispatched along the reactor. Because of this it can be assumed that agitation is correct. The only troubleshooting expected is a short-cut at the bottom of the reactor due to the presence of a bed of glass wool. Because of these information it was proposed a model (Fig. 82) composed by few perfect mixing cells in series with back-mixing (due to the presence of baffles) associated in a parallel which ten perfect mixing cells in series and a small flow-rate, which represent the shortcut.

The excellent agreement between the experiment and theoretical results and the coherence of the parameters demonstrates the validity of the proposed model. The first moment obtained with the simulation is coherence with the experimental one, which can be obtained by the geometrical volume divided by the inlet flow-rate, which confirm also the non-adsorption of the tracer.

4.12.4. Conclusions

Technetium as ^{99m}Tc-pertechnetate can be used as a radiotracer for RTD analysis in anaerobic reactors. This tracer has been used to model the flow behavior in an industrial digester in a sugar WWTP. The obtained model is coherent with the geometrical and physical information available.

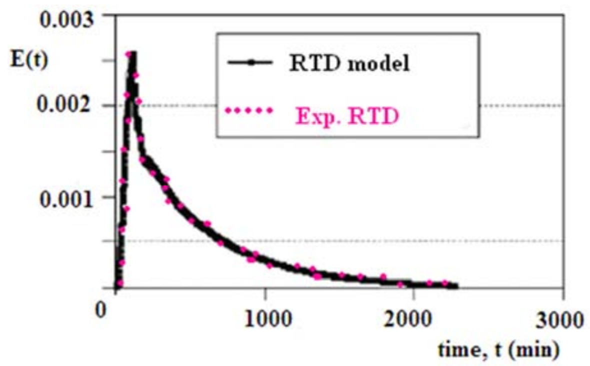


FIG.80. The experimental RTD curve and its model.

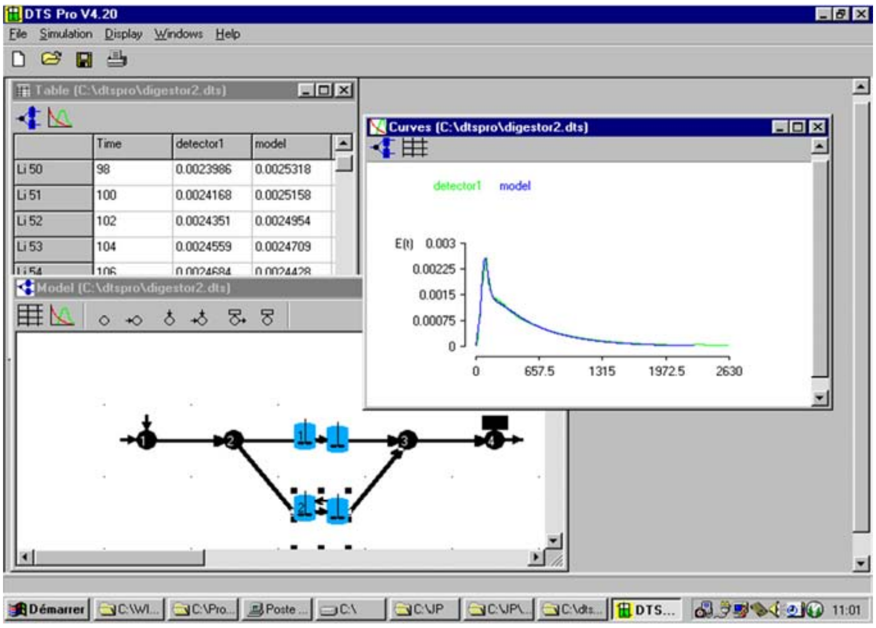


FIG.81. Modeling experimental RTD data with DTS software.

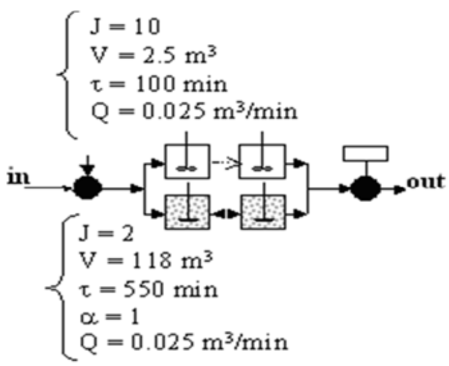


FIG.82. Model of the flow behavior in the first digester.

It was demonstrated, that although the redox potential Eh measured under conditions of anaerobic digestion is not enough to reduce chemically the specie TcO_4^- to $TcO(OH)_2$, Technetium is readily retained with sorption rate of 0.21; 0.83 and 0.045 h^{-1} by three different situations in an industrial digester of a sugar wastewater treatment plant.

It had been proposed that the most probable sorption mechanism is the hold up of Tc by biomass as a result of the metabolization of TcO_4^- and the catalytic reduction by metabolite of the microbiological activity. This mechanism leads to a non-reversible loss of Tc, but due that this does not imply its delay.

4.13. RADIOTRACER INVESTIGATION OF WASTEWATER TREATMENT PILOT PLANT

4.13.1. Evaluation of mixing process in an equalization tank

In a typical WWTP the equalization tank is part of primary treatment, coming directly after the primary clarifier. Its goal is to guarantee the uniformity to the effluent. To study solid/liquid mixture and equalization processes, an experimental equalization tank was built (Fig. 83).

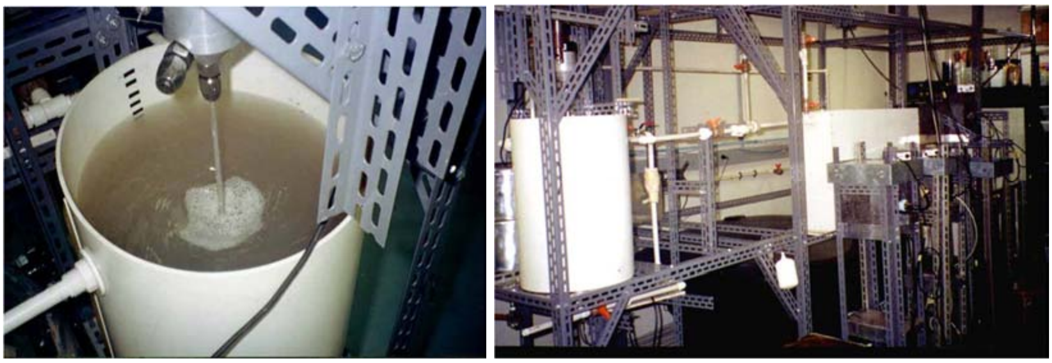


FIG.83. Equalization tank in laboratory scale.

The unit consisted in an 80 liters plastic cylindrical tank with mechanical agitation. Two independents connections, one located in the base and the other in the upper lateral edge of the tank, allow changing the sewer input/output positions. This configuration makes possible to simulate different operation conditions of a real unit. In all radiotracer experiments a scintillator detector NaI(Tl) (2” × 2") was located in the exit of the mixer, shielded by 10.0 cm lead wall and collimated (2.5 cm of diameter). The influent input flow (liquid and solid phase) was 2.5 liters/minute.

Initially an experiment was made to study only the displacement of the liquid phase in the unit. For this, 5.0 mL of NH_4Br (aqueous solution) marked with ^{82}Br (370 MBq) was injected directly in the sewer as a pulse, and its signal measure by the detector. Figure 84 shows the experimental RTD function, E (t), for the equalizer. The curve seems like a perfect mixer but, the measured MRT (22.6min) was 30% smaller than the theoretical value (80/2.5 = 32 min); this could happen when internal canalizations and a dead zone exist inside the tank.

Using RTD software for water flow modeling it was possible to adjust a model for the tank. The model consisted of a perfect mixer with effective volume equal 49.5 liters with internal canalization and a dead volume of 30.5 liters.

To study the equalization process for solid/liquid sewer with different characteristics, the solid phase was separate in two fractions with different granulometry: one, called ‘light fraction’ with 400 mesh and ‘heavy fraction’ less than 150 mesh, respectively marked with ^{110m}Ag and ^{140}La (10 mCi each of them). In the tracer experiments both fractions were injected together in the tank as a Dirac pulse. The experimental RTD curves for ‘light’ and ‘heavy’ fractions are shown in Fig. 85; they differ a lot because the hydrodynamics of both fractions are significantly different.

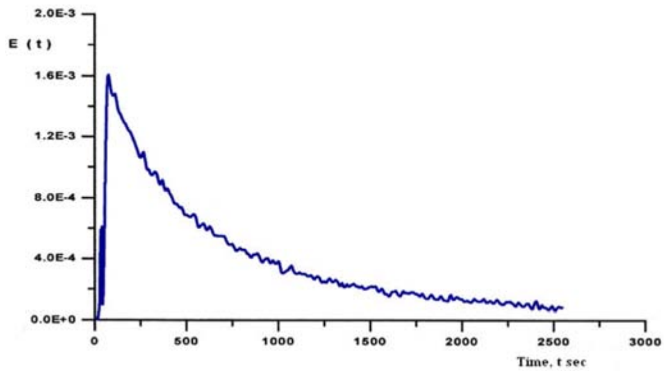


FIG.84.Experimental RTD curve of liquid phase in the equilizer.

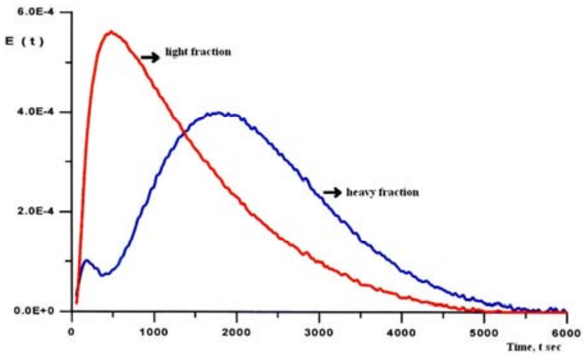


FIG.85. Experimental RTD curves for 'heavy fraction'(^{140}La) and for 'light fraction'(^{110m}Ag).

For the 'heavy fraction', the curve shows a strong canalization process between zero and 400 seconds. This canalization tends to decrease as the 'heavy fraction' goes constantly being mixed and removed and the unit acts as a perfect mixer with effective volume equal to 68.8 liters. With the 'light fraction' there is no canalization or dead zone and the tank acts as a perfect mixer, with the material being slowly homogenized and uniformly removes from the unit. For this fraction, the effective volume is equal 78.7 liters.

4.13.2. Measuring characteristics of a settling tank

To analyze the process characteristics in settling tank of sewage treatment station a Cox laboratory model was built up (Fig.86).

The tank was built in PVC in rectangular form (100.0 × 60.0 × 20.0 cm) with six internal walls (baffle plates of 45.0 × 20.0 cm) resulting in independent compartments where sedimentation process of the solid phase occurs.

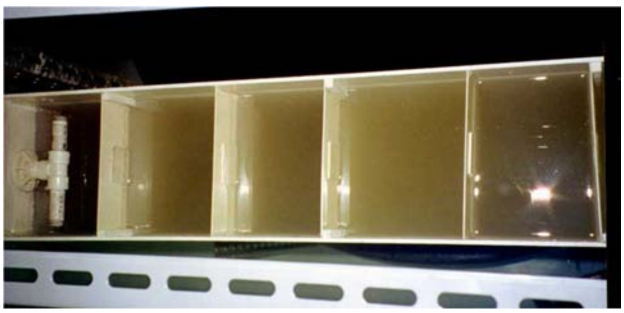


FIG.86. Laboratory settling tank.

Three detectors NaI (2 × 2") were used, which one located in a special position of the tank to measure the movement of the sewage and the deposition of solid phase: the first position (P1) corresponds to the first settling chamber; the second (P2) the fourth chamber and the third position (P3) the exit of the unit. All the detectors were collimated using a lead wall (20 cm) with of 5,0 cm of opening. The sewage solid phase material was collected in a treatment station, dry, separated in two different fractions, heavy and light, and marked with ^{140}La and ^{110m}Ag (10 mCi each of them). In the initial configuration, where each baffle plate in the tank allowed a communication of 15,0 cm between two successive compartments, the results for the displacement of the sewer inside the unit for the detectors are shown in Fig. 87.

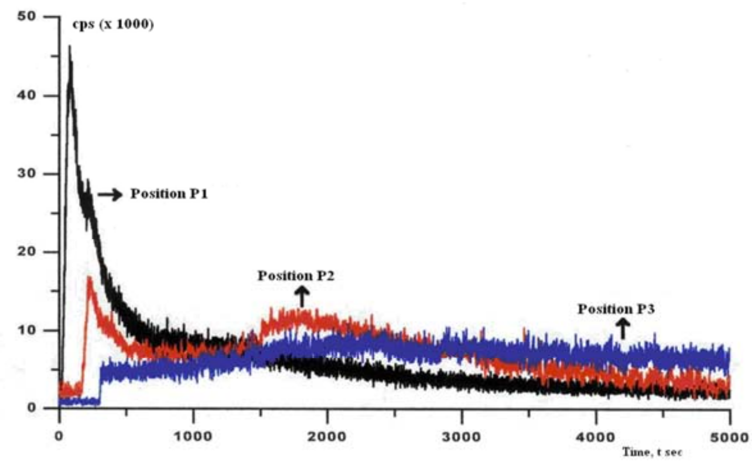


FIG.87. Characteristic curves of setlting tank for original design(single plate).

Signals registered by the detectors in P1 and P2 showed that the setting process of the solid phase was happening inside each compartment but the constant movement of the liquid phase moves these deposits in the bottom toward the exit of the tank. This displacement becomes more evident in the curve P3. After t = 1500 s occurs an increase in the signal registered in the detector P3 due the presence of solid phase marked with radiotracer that this being slowly removed of the unit

In order to improve the efficiency in retention of the solid phase, the baffle plates had been modified. In front of each one, a physical barrier was installed. It consisted of a plain plate separate of the baffle plate by 1,0 cm, which reduces the communication between two successive compartments and hinders the transference of solid material decanted in one chamber for the following one. Figure 107 shows the curves registered by the detectors for this new configuration.

Comparing both situations, it is clear that the second one, with physical barrier is better to improve the removal of the solid phase of the sewer. The curves of P1 and P2 (Fig. 88) shows that a great part of the solid material deposited in the compartments stay in the bottom of the unit. The behavior of the curve of P3 proves the retention of the solid material in the unit, its signal kept approximately to the level of the background until 1000 s, after what, has a lightly increasing, but keeping its intensity low, even around 3500 s and then decrease. This behavior of curve proves the retention of the solid phase in the unit.

The results demonstrate that the technique of radioactive tracers is a useful methodology for the characterization and optimization for this kind of unit. Applying an appropriate tracer make possible to measure the characteristic curve for any kind of unit, identify operational and structural problem and improve the effluent treatment process.

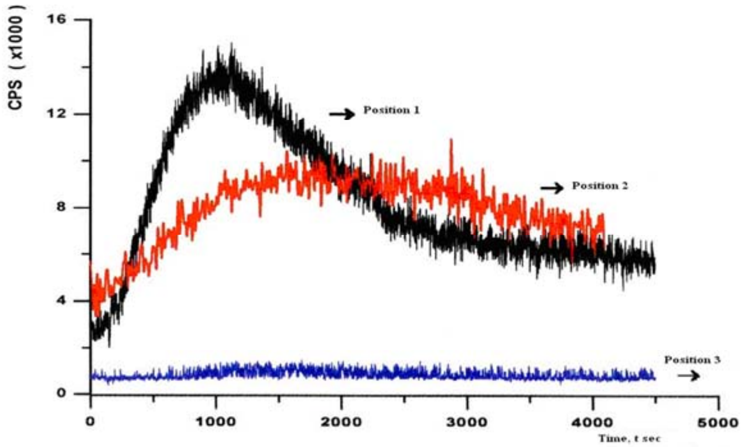


FIG.88. Characteristic curves of setting tank for optimized design(double plate).

4.14. TRACER HYDRODYNAMICS STUDY IN AN AERATION UNIT OF A WASTEWATER TREATMENT PLANT

4.14.1. Problem

Hydraulic behavior in a large activated sludge tank, located at the Rya WWTP in Göteborg Sweden, was investigated by using tracer test and CFD simulation. The Rya WWTP is a high loaded plant located in a small site. Expansion of the site is limited due to several restrictions such as a nearby railway, industrial areas and a nature reserve. An efficient use of already existing facilities is therefore of great importance to meet the demands of effluent discharge.

The dynamics of water through the aeration tank is of fundamental importance for the efficiency of the whole wastewater treatment process. Suspected short circuiting streams and dead volumes may reduce the tank efficiency and thus cause higher residual concentrations in the treated water.

The presence of a short circuiting stream was identified by the experimental RTD curve obtained from tracer test. Computer fluid dynamics (CFD) simulation was employed to evaluate different corrective measures. Inlet baffles were chosen as the preferable alternative. After implementation of baffles, improved tank hydraulics, was verified with another tracer test. The bypass flow was eliminated and the dead volume was reduced. The water dynamics through the aeration tank achieved a more plug-flow character, which is the proper wanted model that provides the higher efficiency.

4.14.2. Tracer test in the aeration unit

The activated sludge process that occurs in the aeration unit is influenced by its hydraulic behavior. The hydraulic behavior is in its turn affected by a number of factors such as; the geometric design of the reactor, the shape and position of the inlet and the outlet, external mixers, baffles, fluid viscosity, aeration and water flow rate.

An unfavorable hydraulic situation in an activated sludge unit may lead to significant reduction of its capacity, thus causing higher concentration of residuals in the effluent. Improper design of a tank can cause short circuiting streams and dead volume. Short circuiting streams means insufficient time for biological reactions to take place and the degree of completion of the necessary biodegrading reactions may therefore be reduced. Any dead volume in the aeration unit also reduces the actual volume available for reactions, thus lowering the capacity of the unit. Thus the mixing characteristics are very important. Reactors with hydraulic behavior approximated to plug-flow produce better settling sludge than completely mixed ones do, and are thus to prefer.

Different tracers have been used in RTD experiments for wastewater bioreactor studies, including soluble salts such as lithium salts, chlorides, dyes, radioactive tracers or microorganisms. Lithium salts are very common tracers because of its low and constant concentration in municipal wastewater and because it is neither degraded nor adsorbed by microorganisms. The LiCl chemical tracer was injected as Dirac puls at the inlet of the aeration tank (Fig. 89). The detection of tracer at the outlet of the system provides the experimental RTD curve.

The aeration system consists of three tanks in series (Fig. 89). Investigation of the hydraulic situation was performed in the first tank. Photos of the first tank are shown in Fig. 90.

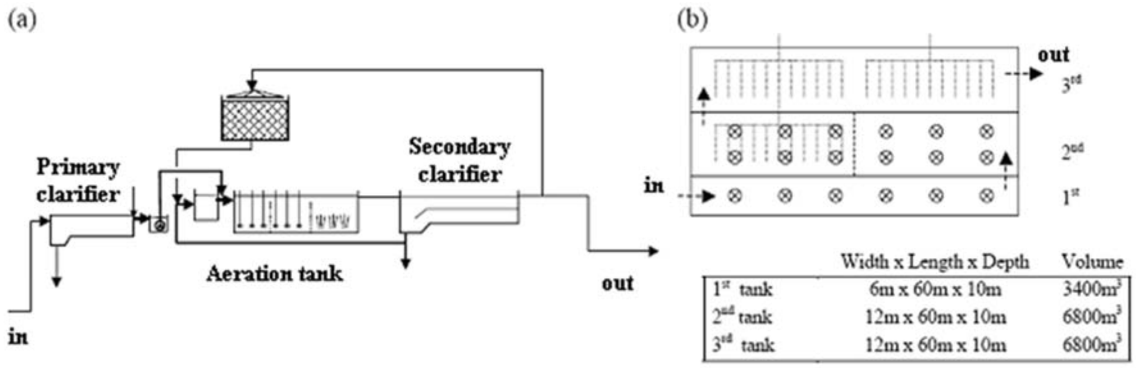


FIG.89. Tracer test in aeration unit, (a) aeration unit design, (b) Aeration unit compartments. Arrows indicate the flow direction.

FIG.90. Photos of the first tank showing the tank without water. The supporting beams and mixers can be seen.

The inlet has an area of 3 m × 2 m and is located in the upper part of the short side of the tank. The outlet (3 m × 5.5 m) is located on one of the long sides at the opposite end of the tank. The fist tank is fitted with six vertical propeller mixers (2 m impeller, 27 rpm). The mixers have a designed pump flow capacity of 108 m^3/min. The second tank is fitted with 12 impellers. Aerators are installed in the second compartment of the tank. The third tank is without impellers. Aerators are installed throughout the tank.

Tracer tests were performed using pulse addition of lithium chloride (LiCl). A mass of 10.0 kg LiCl was dissolved in water and diluted to form a 25 liter brine. The brine was poured into a 50 m long hose. By using pressurized wash-water, the tracer was injected into the inlet of the first tank, all within a few seconds. Approximately 150 samples (100 mL each) were taken during the tracer tests. Samples were taken at four different locations in the activated sludge line: the outlet of the first tank, the outlet of the second tank, the outlet of the third tank and in the channel before entering the basins, this for tracer background level detection. Wastewater flow rate and the air supply to the tanks were stabilized during the tests, as was the recirculated activated sludge flow rate.

The samples were allowed to settle and the supernatant was filtered (1.2 µm membrane filter, Titan 2 HPLC Filter Orange 30 mm) in order to reduce interference of solids. The lithium concentrations of the samples were measured using a flame photometer (Eppendorf ELEX 3631). This was calibrated on site, using final effluent as dilutant when creating a lithium standard curve. Measured lithium values were used for creating RTD curves.

From the first tank, arithmetic mean values based on tracer concentrations from three sample positions in the outlet (centre, upper right downstream corner, lower left upstream corner) were used when plotting the curve.

4.14.3. Results and discussion

Tracer concentrations in the effluent of the three tanks in the train were measured and the results at a total flow rate of 3.6 m^3/s are shown as experimental RTD curves in Fig. 91.

As mentioned, each data point from the first tank was an average of three samples extracted from different levels. The RTD results generated from the effluent of the first tank show an initial lithium concentration peak at θ~ 0.15 (Fig. 91a). The lithium concentration in the effluent of the second and third tanks reached maximum concentration at θ~ 0.85 (Fig. 91b), and θ~ 0.8 (Fig. 91c), respectively.

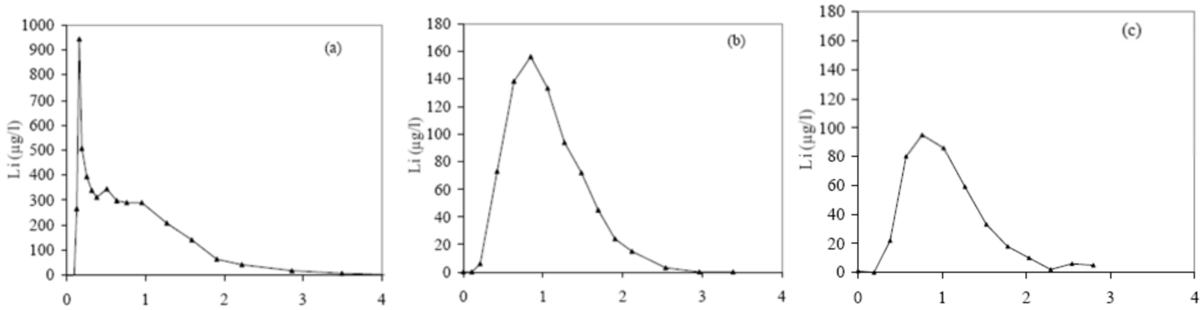


FIG.91. Experimental RTD curves showing lithium concentration detected in the effluent of (a) the first, (b) the second and (c) the third tanks in the tracer test.

The initial peak of the first tank clearly indicates a short circuiting stream. Considering a 10 m deep tank and no baffles, the design likely allows the inlet jet to cause a powerful horizontal short circuiting stream in the upper part of the tank. The tank is fitted with 6 vertical propeller mixers but they are preventing settling and do not affect the short circuiting stream. At a flow of 3.6 m^3/s passing through an inlet cross section of 6 m^2, the mean velocity of the inflow can be estimated to 0.6 m/s. This is a very high velocity. The peak concentration of tracer appears after 2.5 minutes in the 60 m basin, mean velocity of the short circuiting stream can hereby be estimated to 0.4 m/s.

The RTD curves from the second and the third tank have no obvious peaks indicating short circuiting streams. Thus, the short circuit stream in the first tank of the activated sludge reactor is probably suppressed in the following tanks. The passage between the first and second tanks and the second and third tanks is perpendicular to the flow direction, which is favorable for the hydraulics. Furthermore, the aeration of the third tank with bubbles rising from the bottom of the tank, counteract the short-circuiting stream by its traveling perpendicular to the bulk water flow. Focus was concentrated to the first tank due to the presence of short circuiting streams.

The purpose of extracting samples at different positions in the effluent of the first tank was to investigate radial gradients. Tracer concentrations from two positions are plotted in Fig. 92.

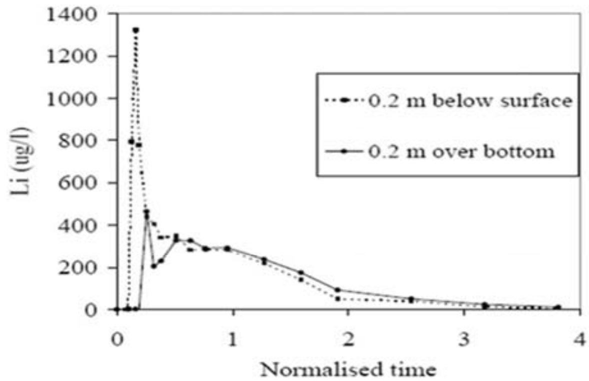


FIG.92. Experimental RTD curves showing radial gradients in effluent of first tank.

Samples extracted 0.2 m below the surface of the effluent stream indicate an initial high peak. However, the lithium concentrations are strictly higher at θ>1 in samples extracted at 0.2 m above the bottom of the outlet (1.4 m below the surface) in the effluent stream. This supports the assumption that the short circuiting stream is located in the upper part of the tank. Recovery of tracer in the effluent of the first tank was almost 100 % of the amount injected to the inlet.

The extracted data from the tracer test was used to calibrate the model for the hydraulic behavior in the first tank. Modeling of the first tank was carried out with a tanks-in-series model, and the model of tanks in series connected in parallel with a dead volume (Fig. 93). The results of modeling are plotted in Fig. 94.

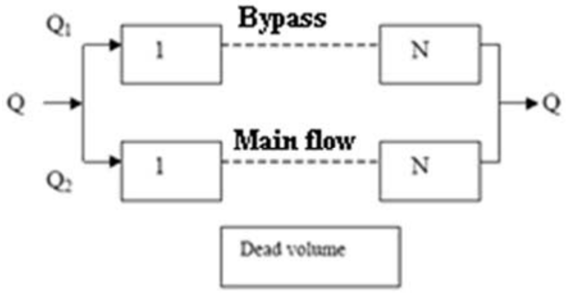


FIG.93. First tank model, tanks in series in parallel with dead volume.

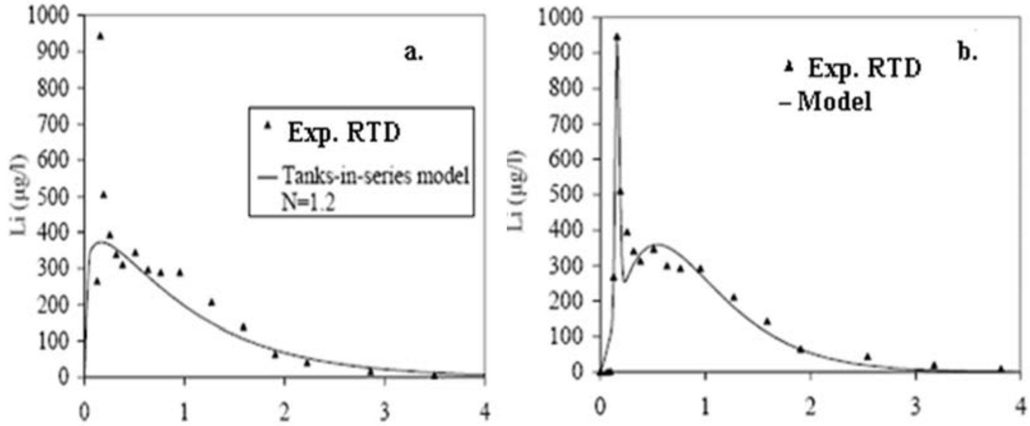


FIG.94. Modeling experimental RTD curve with a. tanks in series, and b. tanks in series in parallel with dead volume models.

As seen from Fig. 94, the tanks-in-series-model does not re-create the short circuiting stream and therefore gave a poor fit. The model of tanks in series connected in parallel with dead volume generates the best fitting. Thus, this model was used to quantify the short circuiting stream and dead volume. At a total flow of 3.6 m^3/s the reactor was characterized with 12.8% dead volume, 85.8% main active volume and 1.3% short circuiting volume. In a similar experiment with a higher flow rate of 4.7 m^3/s, the reactor was characterized with 7.0% dead volume, 88.5% main volume and 4.5% short circuiting volume. It indicates that the short circuiting flow was increased at a higher flow rate.

The CFD simulation was used to generate the RTD response for the first tank. Both RTD curves, tracer experimental one and CFD calculated, fit well (Fig. 95). As shown in Fig. 95, a short high initial peak (after approx. 3 min.) appears indicating short circuiting streams in the tank. The rather long 'tail' of RTD curves indicates areas with poor mixing in the tank (dead volume). In addition, the CFD modeling provides the velocity map inside the aeration tank (Fig. 96).

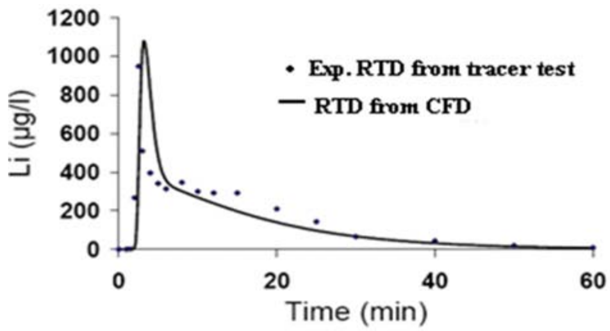


FIG.95. Experimental RTD curve and RTD curve generated from CFD simulation in the first tank.

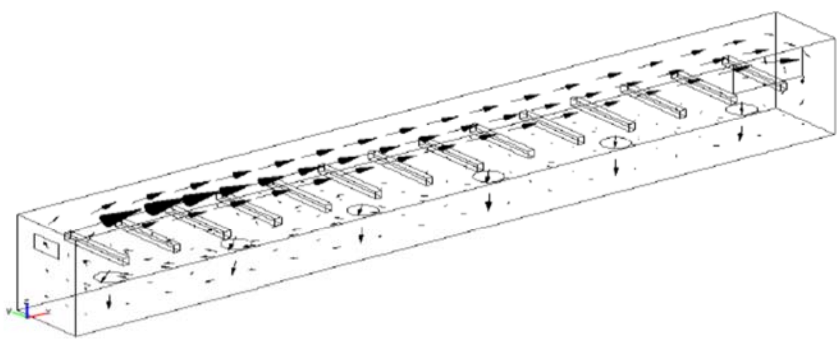


FIG.96. Velocity map obtained by CFD simulation.

The velocity map shows the main flow passing straight through the upper part of the tank; this is most likely caused by the short circuiting stream creating the initial peak in the RTD-curve. Near the bottom the flow seems to be slowly transported back towards the entrance of the tank.

This phenomenon is causing the 'tail' of tracer shown in the RTD-curve and indicating that this part of the aeration tank is not 'active' (dead or stagnant zone). Thus, the six mixers installed to promote mixing in the tank, are obviously not able to make active the whole volume of the aeration tank.

CFD simulation of aeration tank hydraulics was performed to evaluate different corrective measures for improving the process efficiency in aeration tank (reduce bypass flow and dead volume).

RTD curves generated from CFD simulations of different corrective measures are plotted in Fig.97. Figure 98 shows velocity maps obtained by CFD simulations for three different corrective measures.

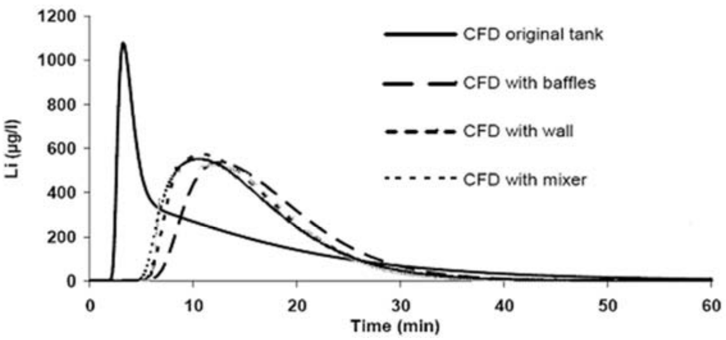


FIG.97. RTD curves generated from CFD simulation for different corrective measures.

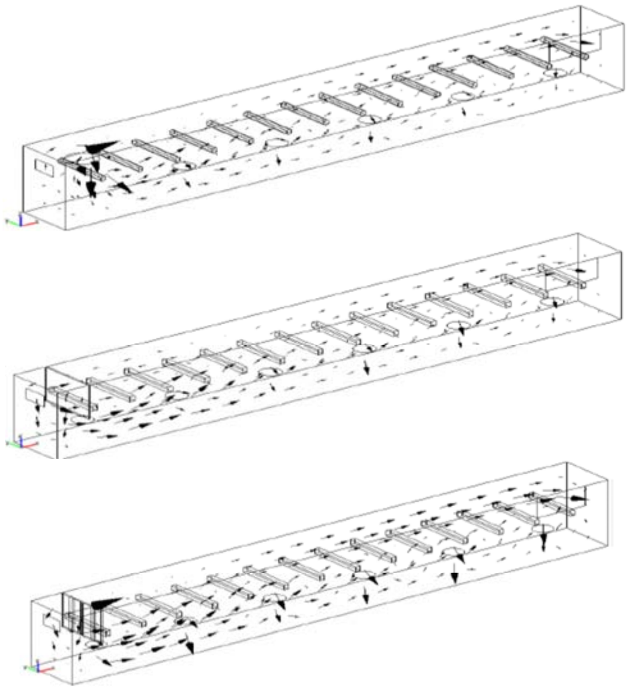


FIG.98. Velocity maps obtained by CFD simulation for three corrective measures.

Three main corrective measures were made:

- installing a powerful mixer near the inlet,
- installing a wall near the inlet.
- installing baffles near the inlet.

All three corrective measures have the capacity to break the short circuiting stream and also reduce the dead zones in the tank. As shown in Fig. 98 the high velocity in the upper part of the tank caused by the inlet jet is neutralized by all of the corrective measures. In the lower part of the tank, the bulk flow rate is increased, which in its turn leads to a decreased dead volume. Installation of baffle was chosen as the best option to improve the hydraulic situation in the aeration tank. Four baffles, each with a length of 5 m (1.2 m wide), were installed at 2.5 m from the inlet. The baffles cover 80 % of the width of the basin and about half of the depth.

Tracer test was conducted after installation of baffles. The experimental RTD curve is given in Fig. 99 (together with the experimental RTD curve without baffles). The initial high peak seen in the original tank is eliminated, thus indicating that no more bypass flow. The 'tail' of the RTD curve is also decreased compared with the original tank. This is indicating that the inactive part of the tank has decreased.

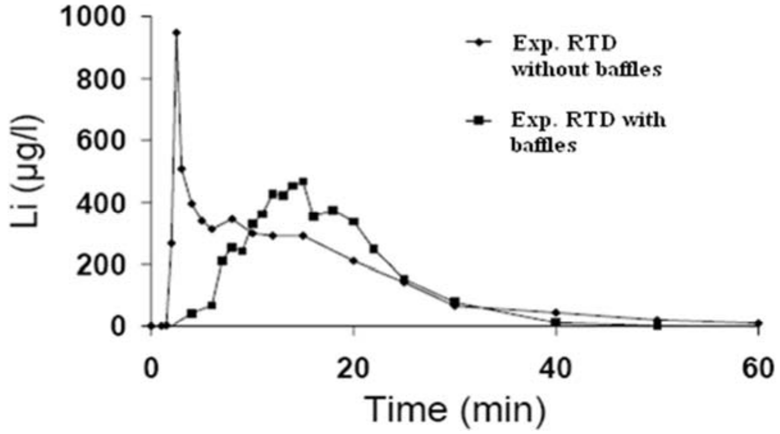


FIG.99. Experimental RTD curves without and with baffles.

4.14.4. Conclusions

- Tracer tests are very informative when investigating hydraulic situations in activated sludge tanks. Utilization of chemical tracers needs a tedious work and claims a lot of personal. For online measurement the radiotracers are more competitive.
- CFD simulation helps analyzing hydraulic behavior in WWTP's units in various situations and assessing the design and effect of different corrective measures, which again should be verified by real tracer test.
- The tracer tests clearly indicated a short circuiting stream in the first tank of the aeration system. The short circuiting stream passed through the upper part of the tank and decreased the efficiency of the tank. This problem became worse at higher inflows to the tank.
- CFD simulations were consistent with the tracer tests confirming the short circuit flow and dead volume.
- Implementation of baffles at the inlet of the aeration tank has eliminated the bypass flow and reduces significatively the dead zone improving the hydraulics performance of the aeration tank.
- Investigation of dynamics of suspended solids through the aeration tank is important for full understanding of the multiphase flow hydraulics inside the aeration tank. Tracer test with solid sediment are necessary in this case. There is no any chemical or fluorescent proper tracer for solid phase. Radiotracers are only available to be utilized in this case. Without tracer test for solid phase, the CFD simulation is powerless to provide a reliable picture of solid phase movement in the aeration tank.

4.15. TRACER HIGH LOAD FIELD TEST OF A SECONDARY CLARIFIER IN A WASTEWATER TREATMENT PLANT

4.15.1. Problem

The secondary (final) clarifier is a very important treatment unit. If it does not fulfill its function properly, the desired effluent quality may not be achieved. Although the clarifier was operating very well, the WWTPs engineers wanted to determine the capacity of the existing secondary clarifier system for the use in planning of any future upgrades. Also, they wanted to know if any upgrades or changes should be considered for the units.

The clarifiers at these plants are peripheral-feed/peripheral-overflow (PF/PO) clarifiers designed for optimum activated sludge secondary clarifier performance. The clarifier is made up of three basic hydraulic components, the inlet channel raceway, the effluent channel and the settled sludge withdrawal header. The test clarifier (Fig. 100) was a 48.75 m diameter split influent flow with dual unitube sludge collection headers. Mixed liquor was fed from an aerated mixed liquor channel.

4.15.2. Tracer test

During tracer test the activated sludge basin was operated in their normal service mode. A fluorescent dye tracer was injected at the inlet, and samples were taken at the outlet (Fig. 100). It was possible to maintain, over an eight hour period, an overflow rate of up to 2.21 m^3/h with a solids loading of up to 243 $kgs/m^2/day$. A series of 'snapshots' of the progression of dye in the tank is shown in Fig. 101. The current progressed uniformly toward the center.

4.15.3. Discussion of tracer results

An ideal settling tank is defined as one that has the characteristics of a plug flow reactor. That is to say, the residence time of an element of flow in that tank is equal to the theoretical detention time at that flow rate. Settling tanks never perform as ideal plug flow. The experimental RTD curves obtained in the secondary clarifiers with normal and high load rate are shown in Fig. 102.

FIG.100. Tracer test in secondary clarifier.

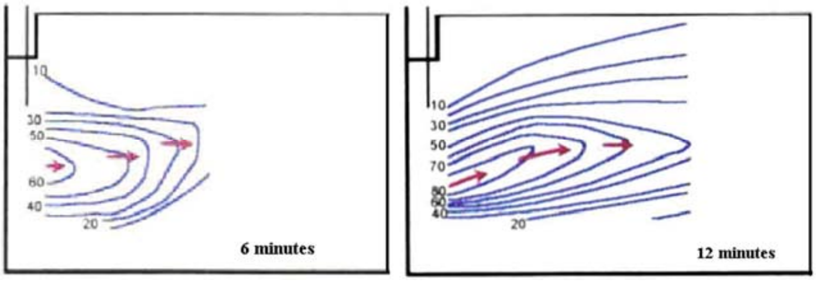


FIG.101. Tracer progression after injection.

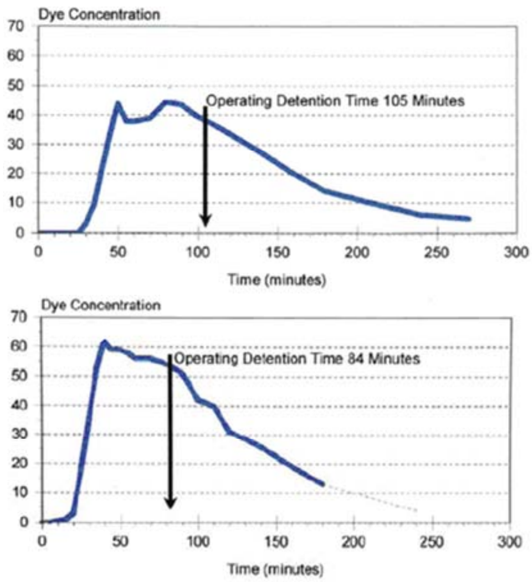


FIG.102. Experimental RTD curves in secondary clarifiers.

The experimental RTD curves obtained by dye tracer test have not long tails that means no significant dead volume ('wall effect') was present during tracer tests in activated sludge secondary clarifiers. Short-circuiting, inherit on all clarifiers, is greatly reduced. In fact, a higher overflow rate reduces the short-circuiting factor by driving the density current further and faster into the basin and away from the weir.

Results of the high load test showed that the clarifier can perform normally at the high rate without any problem.

PRACTICAL RECOMMENDATIONS

The experience has shown that:

- The use of radiotracers appears to be an ideal method of assessing the proper functioning, optimization and the design of various operations in WWTP.
- Different phases such as solid, liquid and gases can be analyzed simultaneously by selecting proper radiotracers.
- In certain applications such as anaerobic digesters, there is no alternative to the use of radiotracer.
- In the case of the sediment transport in various WWTP units such as clarifiers, settlers, digesters, outfalls and treated water discharges, radiotracers are the only tracer option and have proved their utility.
- As most of the WWTP operations are relatively slow as compared to many industrial processes, the data collection time is quite long. Thus, very low level of radiotracer concentration can be used to obtain meaningful data which correctly represent process conditions.
- Radiotracers when chosen properly are completely inert to the microbes present in the digesters and do not interfere with the biological processes and do not introduce additional pollution load unlike conventional tracers.
- The use of radiotracers in WWTP should be promoted vigorously to reduce the adverse environmental impact of the improperly treated wastewater discharge

For a meaningful radiotracer experiment the following steps has to be taken in consideration:

- Collection of the basic data, references and technological knowledge (know-how) about the processes under investigation
- Identification of problems from the chemical and process engineering point of view that have to be solved.
- Look over of the accessible methods for problem solution (including non-radiotracer method).
- Preparation of the experiment methodology:
  - Choice of tracers
  - Methods of experimental data acquisition and processing (hardware, software, graphical presentation of results)
- Validation of results
  - Comparison of the obtained results with registered technological parameters of process under investigation during the experiment (identification of possible technological disturbances).
  - Application (if possible) of other methods for process run evaluation (computational fluid dynamics, laboratory tests, etc.)
- Interpretation of experimental results
  - Evaluation of data errors
  - Technological recommendations concerning the process under investigation

For current users and operators of WWTP the tracer technique helps in:

- Large conglomerates of factories and common effluent treatment plant can use this technique to assess their capacity to treat additional wastewater in line with the expected industrial growth.
- Periodically assessing the proper functioning of WWTP without it having to shut-down and for troubleshooting.
- Planning in advance for the annual shut-down and identify the operations requiring critical improvements.
- Periodic calibrating of pumping devices for flow rates.
- Optimizing of equipment design and discharge for minimum adverse environmental impact.

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ABBREVIATIONS

WWTP	waste water treatment plant
RTD	residence time distribution
MRT	mean residence time
CSTR	continuously stirred tank reactor
DV	dead volume
CFD	computer fluid dynamics
EDTA	ethylenediamine tetraacetic acid
UV	ultraviolet

CONTRIBUTORS TO DRAFTING AND REVIEW

Brandao, L.E.B.	Instituto de Engenharia Nuclear, Cidado Universitaria, Rio de Janeiro, Brazil
Brisset, P.	DIMRI-LIST, CEN-Saclay, France
Chmielewski, A.	Department of Nuclear Methods of Process Engineering, Institute of Nuclear Chemistry and Technology Warsaw, Poland
Genders, S.	FORCE Technologies , Copenhagen, Denmark
Griffith, J.M.	Instituto Cubano de Investigaciones Azucareras (ICINAZ) Departamento de Tecnicas Nucleares, Havana, Cuba
Jin, J-H.	International Atomic Energy Agency
Khan, I. H.	Pakistan Institute of Nuclear Science and Technology (PINSTECH) Radiation and Isotope Applications Division (RIAD) Islamabad, Pakistan
Kjellstrand R.	Department of Chemical Reaction Engineering, Chalmers University of Technology, Göteborg, Sweden
Palige, J.	Department of Nuclear Methods of Process Engineering, Institute of Nuclear Chemistry and Technology Warsaw, Poland
Pandit, A.	University Institute of Chemical Technology (UICT), Mumbai, India
Pant, H. J.	Bhabha Atomic Research Centre, Mumbai , India
Sung-Hee Jung	Radiotracer Project, Korea Atomic Energy Research Institute (KAERI) Daejon, Republic of Korea
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