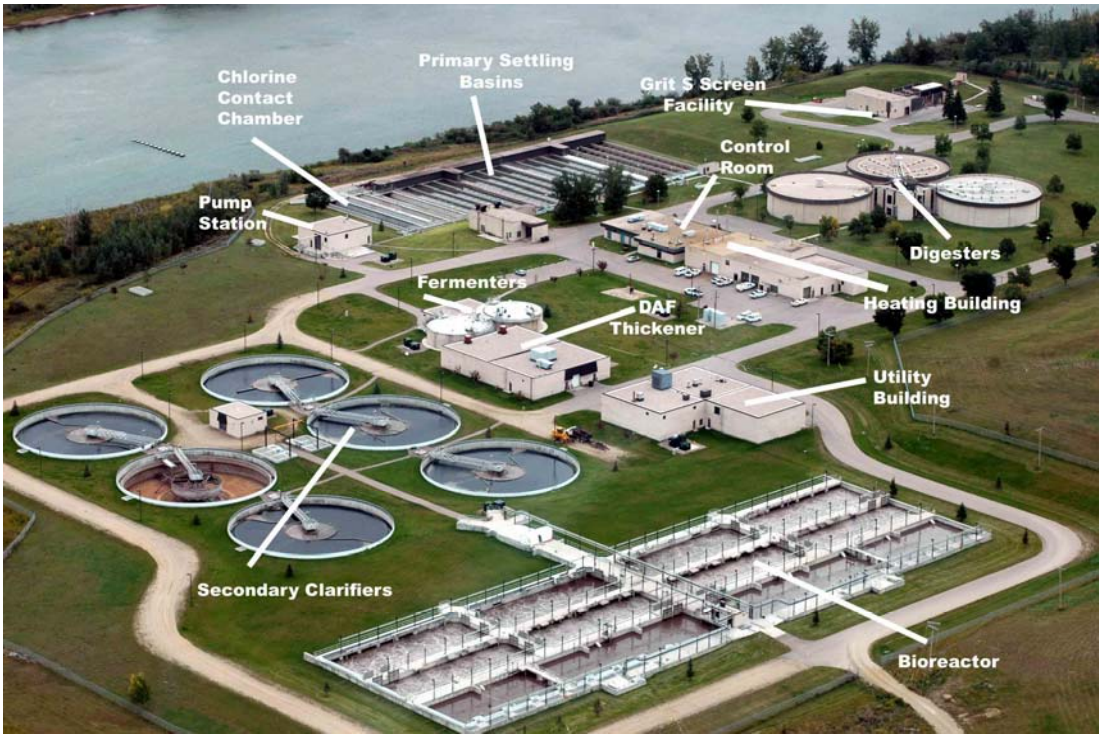
Brochure

Radiotracer applications in wastewater treatment plants



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FOREWORD

Wastewater is liquid waste that comprises a mixture of domestic sewage and industrial effluents. Wastewater generally contains high levels of organic material, numerous pathogenic microorganisms, as well as nutrients and toxic compounds. It thus entails environmental and health hazards, and, consequently, must be treated appropriately before final disposal. At wastewater treatment plants (WWTP) the wastewater is run through a multi-stage treatment process to clean it before discharge into the environment or reuse. Physical, chemical and biological methods are used to remove contaminants from wastewater. The ultimate goal of wastewater management is the protection of the environment in a manner commensurate with public health and socio-economic concerns.

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 their extremely high detection sensitivity, and the strong resistance against severe process conditions.

Thousands of WWTPs are in operation all over the world, other hundreds are in process of design and construction. Many developing countries practice wastewater treatment and reuse. Treated wastewater is widely reused for irrigation, particularly in the arid and semi-arid countries; at the present time, millions of cubic meters per day generated from WWTP are used to meet irrigation needs. This aspect does indicate that optimal design and performance of WWTP are very important issues for both developed and developing countries.

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 been compiled yet. 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 not been established by international tracer community either.

The brochure on radiotracer applications in WWTP amply demonstrates the extensive use of tracer techniques for investigating liquid and solid transport models in wastewater purification installations. This technical document will help the radiotracer groups in Member States to promote and apply the radiotracer technology for better serving the environmental sector.

Many outstanding specialists all over the world have contributed in drafting of this material. Mr. J. Thereska, consultant, has compiled it. The IAEA wishes to thank all the specialists for their valuable contributions.

The IAEA officers responsible for this publication are Mr. Dias P.M., from the Department of Technical Cooperation, and Mr. Jin, Joon-Ha, technical officer of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

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1. INTRODUCTION

A wastewater treatment plant (WWTP) is basically 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. Radiotracers are tool of choice for following liquid and sediment transport. The success of radiotracer applications rests upon extremely high detection sensitivity facilitating their use in large scale WWTP treating millions of liters of effluent, and the strong resistance against severe process conditions.

The wastewater sources can be broadly classified as domestic sewage and industrial effluent. Wastewater is 99.9% water, with a small amount of dissolved or suspended solid matter. The cloudiness of sewage is caused by suspended particles which in untreated sewage ranges from 100 to 350 mg/l. The quality of the wastewater, the type and the level of contamination existing in the source are widely different and hence the treatment strategy for each of this wastewater is significantly different.

Sewage treatment is a multi-stage process which goal is to reduce or remove organic matter, solids, nutrients, disease-causing organisms and other pollutants from wastewater. It includes physical, chemical and biological processes to remove physical, chemical and biological contaminants. The site where the raw wastewater is processed before it is discharged back to the environment is called a Wastewater Treatment Plant (WWTP), or less used Sewage Treatment Plants (STP) (Fig. 1).

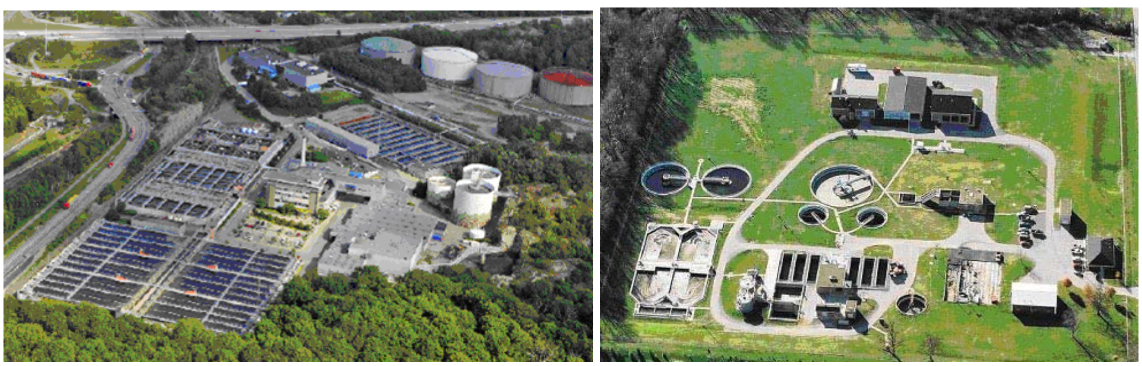


FIG.1. View of some medium(left) and small (right) size WWTPs

The types of mechanical, physical, chemical and biological systems that comprise different kinds of WWTPs are typically the same:

- Mechanical treatment: Removal of large objects, sand and grit
- Physical treatment: Pre-precipitation and post precipitation
- Biological treatment: aeration to accelerate the oxidation process,
- Chemical treatment.

Why do research about something as filthy and stinky as a wastewater treatment process? Well, firstly, it is commonly known that clean water is a limited resource of which one must take good care. Water is used mainly for three purposes; agriculture, industry and domestic use. This means that huge amounts of wastewater are produced every day. Nature itself has a fantastic ability to cope with small amounts of wastewater and pollution, but if there were no wastewater treatment plants (WWTP's), this natural system would be completely overloaded. WWTP's are in short used to reduce pollutants in wastewater to a level which nature can handle.

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, and (2) the strong resistance against severe process conditions.

This brochure provides principle operations occurring in the WWTP and basic wastewater treatment technologies. The brochure gives insight to radiotracer methodology and technology as applied to WWTP and discusses the 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 fairly well established and many case studies described in the brochure illustrate the advantages and benefits of radiotracer applications in WWTP.

The brochure is intended to serve the needs of

- Radioisotope practitioners in nuclear centers or private companies for their on job training in these particular radiotracer techniques,
- Radiotracer groups to promote and introduce the radiotracer technology to environmental sector, and provide routine services for problem solving,
- Engineers and managers of industry and environment to understand the potential of radiotracer techniques for investigating and optimizing the WWTP.

The first part (chapters two and three) illustrates various wastewater treatment technologies. Technical details on major treatment methods and processing units are presented. Tracers and radiotracers for diagnosing WWTP units are introduced in part two (chapters four and five). 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 with simulation by computer fluid dynamics (CFD) is presented. Part three (chapter six) discusses the radiotracer techniques as applied to investigation of WWTP' units. Real case studies are given. The chosen applications represent the major problems of WWTP where the radiotracers are very competitive and sometimes unique to solve the problem. Although these cases are included as illustrations, this is not intended as a bibliography of applications. Encouraging utilization of radiotracers as most competitive for on-line and multitracer investigation in WWTP, the brochure presents also case studies where other tracers are used instead of radiotracers, mostly due to public acceptance and strict regulations in some countries. It is expected that the radiotracers largely used in nuclear medicine diagnosis (Tc-99m, I-131, I-125 and In-113m) will be playing the same role and have the same acceptance in the diagnosis of WWTP units in the near future as well.

2. PRINCIPLES OF WASTEWATER TREATMENT

Wastewater comprises a mixture of domestic sewage (waste from household toilets, sinks, showers and washing machines), industrial effluent, occasional run-off of surface water and ground water which has infiltrated into the sewers. Wastewater is 99.99% water, with a small amount of dissolved or suspended solid matter.

Wastewater (or sewer) is treated in similar ways all over the world, but the levels differ. Commonly there are three main steps in the wastewater treatment process; a preliminary step, a primary step and a secondary step (Fig. 2). The preliminary step includes screening (removal of larger objects and grit). Suspended solids are then removed by settling in the primary clarifier (as raw or primary sludge). Biological degradation of non-settled organic materials is achieved in the aeration tank of the secondary treatment. Activated or bio-sludge formed in the aeration tank is removed by settling in the secondary clarifier. After these two treatment steps, the remaining water (so called "secondary effluent") could be discharged into the environment, and the sludge may be disposed somewhere. However, in many medium sizes WWTP's there is also a tertiary treatment step for secondary effluent disinfection, as well as an advanced treatment for sludge's.

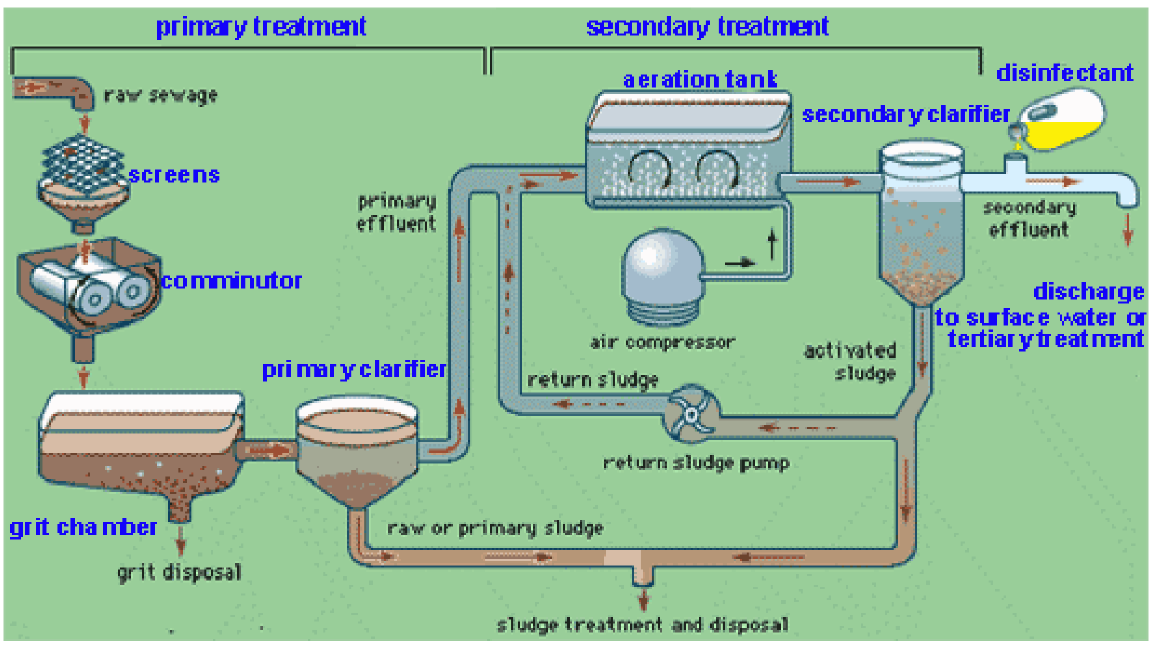


FIG.2. Principle of a WWTP

There are different designs of WWTPs. Fig. 3 presents a simplified flow chart and main processing units for a complete wastewater treatment system. The wastewater is run through a multi-stage treatment process to clean it before discharge into the environment or reuse. Generally, there are five major steps for treatment of wastewater.

FIG.3. The main processes in a WWTP

1. Preliminary treatment, screening of solid materials

The first stage of the treatment process uses screens to remove the larger solid inorganic material such as paper and plastics (Fig. 4). This is followed by the removal of particles such as grit and silt which are abrasive to plant equipment.

FIG.4. Wastewater preliminary treatment, to remove large solid material (left) and grit (right)

2. Primary treatment, settling tank or primary clarifier

Following preliminary treatment, wastewater is passed through a primary sedimentation tank where solid particles of organic material are removed from the suspension by gravity settling. Most of the settleable solids and a large amount of the suspended solids settle to the bottom of the tanks. The settled (raw or primary) sludge is moved to the hoppers by means of a sludge scraper mechanism.

FIG.5. Primary clarifier tanks (left) and lagoons (right)

In a typical WWTP an equalization tank is following the primary clarifier; the equalization tank has the objective to guarantee a uniformity of the effluent (physical/chemical properties more constants in the subsequent stages), facilitating the operational control of the plant.

3. Secondary treatment

a. Secondary treatment, biological aeration tank

This next stage is a biological process which breaks down dissolved and suspended organic solids by using naturally occurring micro-organisms. It is called the activated sludge process. The settled wastewater enters aeration tanks where air is blown into the liquid to provide oxygen for mixing and to promote the growth of micro-organisms. The "active biomass" uses the oxygen and consumes organic pollutants and nutrients in the wastewater to grow and reproduce. A solid organic material (sludge= "active biomass") is created.

FIG.6. Biological aeration tank and its closeup

b. Secondary clarifier

From the aeration tanks, the bio-system mixed liquor passes into a sedimentation tank (also known as secondary clarifier) where the biomass settles under gravity to the bottom of the tank and is concentrated as sludge. Some of this sludge is recycled to the inlet of the aeration tank to maintain the biomass. The activated sludge could be disposed somewhere (in small size WWTP) or is pumped to anaerobic digesters for further treatment (in medium size WWTP). The clarified wastewater may be discharged from the secondary clarifier to surface water or goes for disinfection.

FIG.7. Secondary clarifier, in operation (left) and after removing water (right, sludge layer is there)

FIG.8. Clarified water is discharged out of secondary clarifier (left), while the sludge remains for drying (right)

4. Tertiary treatment (disinfection): In a full treatment WWTP the "clarified water" passes further for tertiary treatment to reduce pathogens, which are micro-organisms that can pose a risk to human health (Fig. 9). Chlorine is usually dosed into the treated wastewater stream for disinfection. In some cases, the UV light is employed to reduce the pathogens. The treated wastewater can be reused for irrigation of food crops.

FIG.9. Tertiary treatment (disinfection) with chlorine (left) or UV light (right)

5. Sludge treatment

Sludge (muddy sediment, biosolids or biomass) is one of the final products of the treatment of the sewage at wastewater (sewage) treatment plant. It is defined as: "A viscous, semi-solid mixture of organic matter, bacteria, toxic metals, synthetic organic chemicals, and settled solids removed from domestic and industrial wastewater at sewage treatment plants." Sludge originates from the process of treatment of wastewater. 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 (Fig. 10) heated to 35 degrees Celsius, where anaerobic micro-organisms thrive without any oxygen.

FIG.10. Different models of Anaerobic digestors

There are several ways that sludge is used. A state in the USA has reported as follows. An estimate 50% of the sewage sludge is applied to agricultural land, 18% is composed or palletized and made into commercial soil supplement, and 21% is used for land reclamation such as restoring surface mines. The remaining 11 % is disposed in landfills or incinerated.

Anaerobic digestion has a great future amongst the biological technologies which will become the tools for sustainable waste management throughout the 21st Century, working with nature to maintain the natural carbon cycle to the benefit of man.

3. WASTEWATER TREATMENT TECHNOLOGIES

3.1. WASTEWATER TREATMENT METHODS

Physical, chemical and biological methods are used to remove contaminants from wastewater. In order to achieve different levels of contaminant removal, individual wastewater treatment procedures are combined into a variety of systems, classified as primary, secondary, and tertiary wastewater treatment. Natural systems are also used for the treatment of wastewater in land-based applications. Sludge resulting from wastewater treatment operations is treated by various methods in order to reduce its water and organic content and make it suitable for final disposal and reuse.

Wastewater treatment unit operations and processes are:

- Physical unit operations:
    - Screening
    - Flow equalization
    - Sedimentation
    - Flotation
    - Granular medium filtration

- Chemical unit operations:
    - Chemical precipitation
    - Disinfection

- Biological unit operations:
    - Aerobic activated sludge process
    - Anaerobic digestion

3.1.1. Physical unit operations

Among the first treatment methods used were physical unit operations, in which physical forces are applied to remove contaminants. Today, they still form the basis of most process flow systems for wastewater treatment.

(a) Screening

The screening of waste-water, one of the oldest treatment methods, removes gross pollutants from the waste stream to protect downstream equipment from damage. Screening devices may consist of parallel bars, rods or wires, grating, wire mesh, or perforated plates, to intercept large floating or suspended material. 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 secondary and advanced wastewater treatment processes by leveling out operation parameters such as flow, pollutant levels and temperature over a period of time. Variations are damped until a near-constant flow rate is achieved, minimizing the downstream effects of these parameters. Flow equalization may be applied at a number of locations within a wastewater treatment plant, e.g. near the head end of the treatment works, prior to discharge into a water body, and prior to advanced waste treatment operations.

(c) Sedimentation

Sedimentation, a fundamental and widely used unit operation in wastewater treatment, involves the gravitational settling of heavy particles suspended in a mixture. 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). Sedimentation takes place in a settling tank, also referred to as a clarifier. In designing a sedimentation basin, it is important to bear in mind that the system must produce both a clarified effluent and a concentrated sludge. Fig. 11 shows some typical settling basins.

The secondary (final) clarifier follows the aeration unit. The secondary clarifier must not only produce an effluent of acceptable quality, but must also produce underflow sludge of sufficiently high solids concentration. Highly concentrated waste sludge is also desirable from a sludge dewatering and treatment economics standpoint. 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.

In general, two are the main designs of sedimentation tanks for the primary clarifiers, the rectangular shape and circular one.

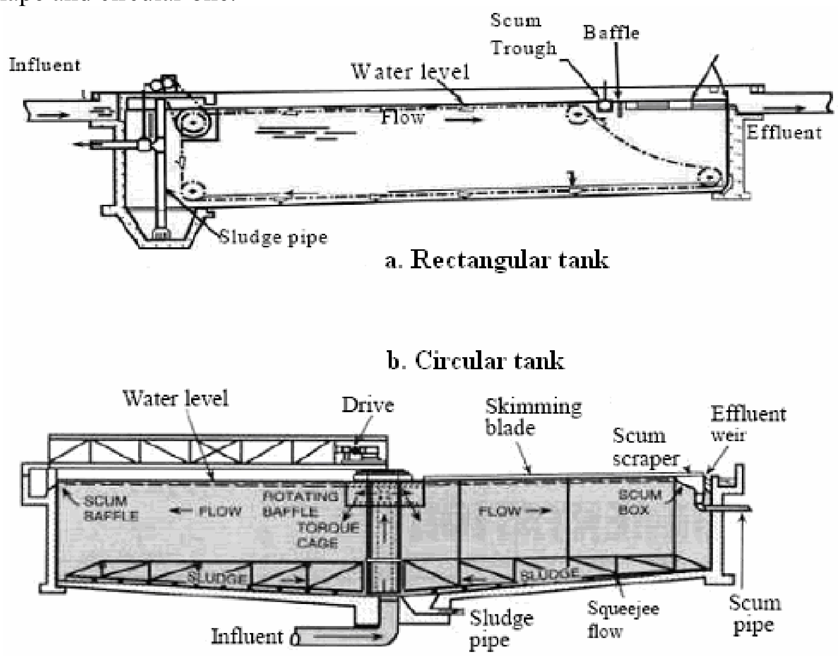


FIG.11. Typical settling tanks or sedimentation units

The design of secondary clarifier is more complicate and still controversial. There are circular secondary clarifiers of the center feed design, and peripheral-feed/peripheral-overflow (PF/PO) clarifiers. The peripheral-feed/peripheral-overflow (PF/PO) mode (Fig. 12) is designed for optimum performance of the activated sludge secondary clarifier. The clarifier is made up of three basic hydraulic components, the inlet channel raceway, the effluent channel and the settled sludge withdrawal header.

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.

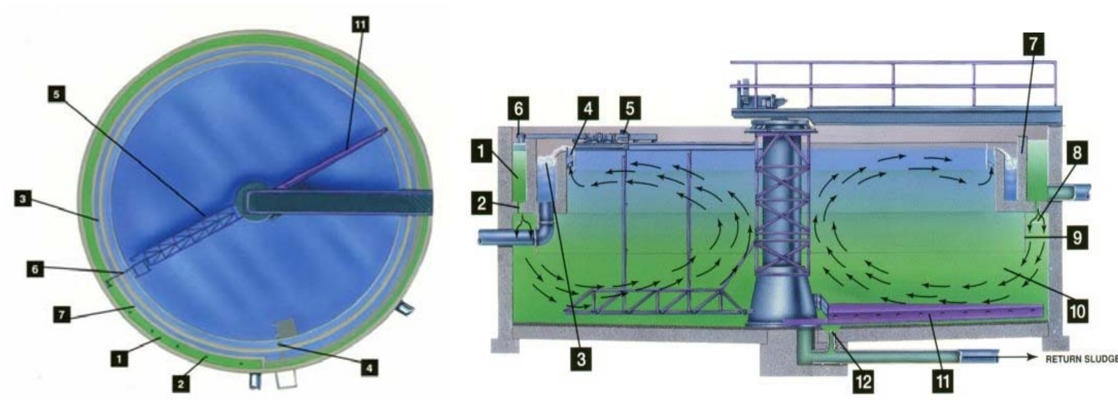


FIG.12. Secondary clarifier: peripheral-feed/peripheral-overflow (PF/PO) model

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.

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 300 to 475%. Improved performance was attributed, in part, to a 7 to 9 time's reduction of inlet velocities into the clarification zone. Solids can build up in settling tanks where this is insufficient mixing to keep the particles suspended.

Despite a wealth of published information on clarifiers' performance, designers are frequently at odds as to the optimal design of both basin and equipment. Designers often rely on antiquated design standards without an understanding of what the key design parameters are or how varying characteristics influence performance. A contributing factor to the wide variance in preferred designs has been a lack of an agreed testing protocol and standardized reporting method. Tracer is the only tool to document performance of the clarifiers.

(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 a relatively recent practice, but has come to be widely used for the supplemental removal of suspended solids. The wastewater to be filtered is passed through a filter bed consisting of granular material (sand, anthracite and/or garnet).

3.1.2. Chemical unit 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.

In general, chemical unit processes have an inherent disadvantage compared to physical operations in that they are additive processes. That is to say, there is usually a net increase in the dissolved constituents of the wastewater. This can be a significant factor if the wastewater is to be reused.

(a) Chemical precipitation

Chemical coagulation of raw wastewater before sedimentation promotes the flocculation of finely divided 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 quantity of chemicals 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 micro-organisms. 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 the following:

(i) Physical agents such as heat and light;
(ii) Radiation, mainly gamma rays;
(iii) Chemical agents including chlorine and its compounds, bromine, iodine, ozone, phenol and phenolic compounds, alcohols, heavy metals, dyes, soaps and synthetic detergents, quaternary ammonium compounds, hydrogen peroxide, and various alkalis and acids. The most common chemical disinfectants are the oxidizing chemicals, and of these, chlorine is the most widely used.

3.1.3. Biological unit processes

Biological unit processes are used to convert the finely divided and dissolved organic matter in wastewater into flocculent settleable organic and inorganic solids. In these processes, micro-organisms, particularly bacteria, convert the colloidal and dissolved carbonaceous 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 may be classified as aerobic and anaerobic processes.

(a) Aerobic activated-sludge process

The activated-sludge process is an aerobic, continuous-flow system containing a mass of activated micro-organisms that are capable of stabilizing organic matter. The process consists of delivering clarified wastewater, after primary settling, into an aeration basin. An aerobic environment is maintained in the basin by means of diffused or mechanical aeration, which also serves to keep the contents of the reactor (or mixed liquor) completely 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 and inorganic 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 varying periods of time. The two most widely used types of anaerobic digesters are standard-rate and high-rate. In the standard-rate digestion process, the contents of the digester are usually unheated and unmixed, and are retained for a period ranging from 30 to 60 days.

In the high-rate digestion process, the contents of the digester are heated and mixed completely, and are retained, typically, for a period of 15 days or less. A combination of these two basic processes is known as the two-stage process, and is used to separate the digested solids from the supernatant liquor. Anaerobic digesters are commonly used for the treatment of sludge and wastewaters with high organic content. An advantage of this type of system is the production of methane gas, which can be used as a fuel source, if produced in sufficient quantities.

3.2. PRIMARY PROCESSES AND UNITS

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 fecal solids can settle and floating material such as grease and oils can rise to the surface and be skimmed off. The main purpose of the primary stage is to produce a generally homogeneous liquid capable of being treated biologically and a sludge that can be separately treated or processed. Primary settlement tanks are usually equipped with mechanically driven scrapers that continually drive the collected sludge towards a hopper in the base of the tank from where it can be pumped to further sludge treatment stages.

3.2.1. Collection of different effluent streams from independent sources coming up to WWTP

The mixing process can be realized depending on specific application on batch wise or in continuous mixers with mechanical rotating devices or by jet of liquid. Possible radiotracers applications are:

- Measurement of flow rates by radiotracer dilution method
- Mass balances.

The first physical operation, which is carried out on the incoming effluent is to remove coarse particles and other floating rubbish materials such as plastic pieces, loose sheets and bags etc.

This is achieved by allowing this water 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 effluent, which is now devoid of large solid particles go to an oil and grease trap where the floating on lighter liquid impurities, such as oil and grease layer is continuously skimmed from the top to reduce the unnecessary organic contaminant load on subsequent operations. Since, both of the above mentioned operations being relatively fairly gross in nature sophisticated technique, such as the use of radiotracers is not very useful at this stage and hence not recommended.

3.2.2. Flocculants and coagulants pre-mixture

For increasing the efficiency of particle separation from wastewater, some chemicals are added. The continuous process of addition of these components is realized in small (Volume $\approx$10 m^3) tanks, which are intensively agitated. The radiotracer method can be used for validation of mixing intensity (efficiency). Inorganic ($Al_2(SO_4)_3$, $Fe_3(SO_4)_2$ etc.) or organic (polyacrylamides) coagulants and flocculants are added to the effluent coming out of the equalization tank and are quickly mixed in a small high intensity vessel called flash mixer having a very small residence time (few seconds or at most a minute). The goal of the coagulant and flocculants is to reduce the surface change 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 effluent through the flash mixer goes to primary clarification where gentle agitation on very low velocity liquid circulation, increase the flocks collision frequency, making them grow in size and are allowed to settle in the conical section of the clarifier. A low speed scraper arm at the bottom of the clarifier/sludge thickener aids the collection and removal of these flocks from the bottom of the clarifier. Fig. 13 shows a standard rectangular clarifier.

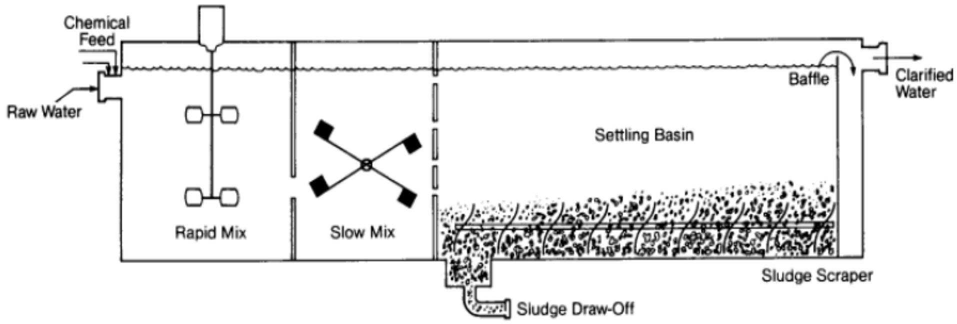


FIG.13. Rectangular primary clarifier with flocumant and coagulant premixture

3.2.3. Primary clarifier

The process of primary clarification is realized in circular clarifiers with diameters D≈20~40 m, depth H≈2~3 m and bottom inclination about 1.50. The different solutions of wastewater input and output are used. 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 but some others solutions are also used. In clarifier, the process of sedimentation takes place.

The scraper localized in bottom zone of tank dislocates the sediment to the centre of clarifier where it is removed. The clarifier represents the two phases (liquid-solid) flow apparatus. The strong interdependence of both phases on the overall flow structure is observed. For technological point of view in the bottom part of clarifier, the presence of flow stagnation zone is required, but in reality, depending on the wastewater flow rate various flow structures have been observed.

The volume of clarifier, V[m^3], 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.

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 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).

The turbidity level (unsettled flock concentration) expected from a well performing clarifier is around 250 ppm., which is very difficult to measure on-line using optical methods and hence solid labeled radiotracers are ideal for this application.

3.2.4. Equalization tanks

The continuously working equalization tanks are intended to equalize chemical composition and if it is possible 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 are largely fluctuating. Equalization system comes in the primary treatment of the wastewater, just after primary clarifier and before aeration tank (Fig. 14).

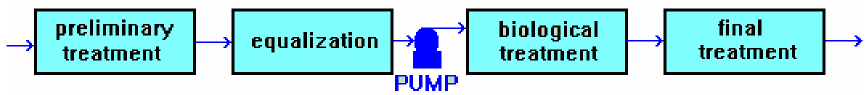


FIG.14. Equalization tank position

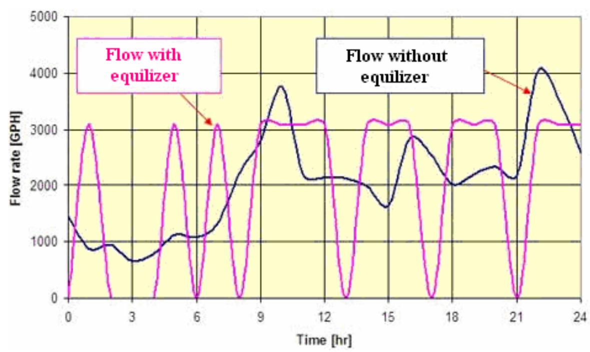


FIG.15. Effect of equalization tank in flow fluctuations

The purpose of an equalization holding system is to smooth fluctuations before sending the wastewater on to the aeration system. 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. The graph (Fig. 15) shows the flow fluctuation with and without equalization tank.

Equalization tanks or holding, equalization lagoons come in all sizes and shapes. They may be small or very large. Mostly, in medium size WWTP, the process of equalization is realized in circle equalizers with volume $V \approx 5000$ m^3 and flow rates $Q \approx 100 \sim 300$ m^3/h. 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 as much uniform as possible.

A common method for combining aeration and mixing is to have a mixer at the surface to splash the liquid into the air. Because the level is changing, this mixer must be mounted on floats. 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.

3.2.5. Sand filters

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 (it does not contain dissolved contaminants).

Usually a polishing sand filter is used at this stage to reduce the outgoing turbidity level to less than 10 ppm. 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.

3.2.6. Disinfection unit

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. These disinfection devices are usually standard gas-liquid contacting devices such as bubble columns, packed columns, liquid jet ejectors etc. and are well analyzed and studied in the chemical industry. In certain cases secondary degassing may also be required (especially in the case of chlorine based disinfection) to avoid the harmful effect of the residual chlorine on the secondary biological treatment. Radiotracers can be used for determination all the technological parameters which describe these type of unit (residence time of both phases, mixing intensity, mass exchange coefficients).

3.3. SECONDARY PROCESSES AND UNITS

Secondary treatment is designed to substantially degrade the biological content of the sewage such as are derived from human waste, food waste, soaps and detergent. The majority of municipal and industrial plants treat the settled sewage liquor using aerobic biological processes. For this to be effective, the biota requires both oxygen and a substrate on which to live. The secondary processes are carried out in two units: aeration tank and second clarifier (Fig.16).

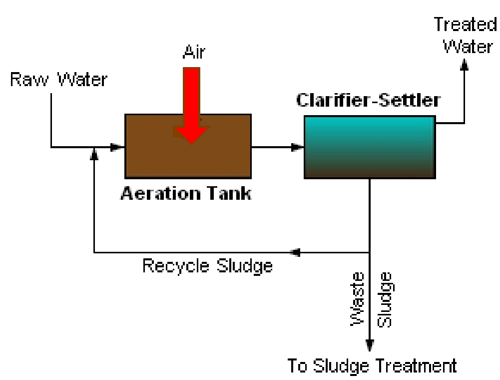


FIG.16. Secondary processes and units

3.3.1. Biological treatment units

In biological chambers the chemical compounds are removed from wastewater by microorganisms in the presence of sufficient quantity of oxygen (aerobic processes). Most biological oxidation processes for treating industrial wastewaters have in common the use of oxygen (or air) and microbial action. Surface-aerated basins may range in depth from 1.5 to 5.0 meters and utilize motor-driven aerators floating on the surface of the wastewater (Fig. 17). Generally, the retention times are 1 to 10 days. In an aerated basin system, the aerators provide two functions: they transfer air into the basins required by the biological oxidation reactions, and they provide the mixing required for dispersing the air and for contacting the reactants (that is, oxygen, wastewater and microbes).

However, they do not provide as good mixing as is normally achieved in activated sludge systems and therefore aerated basins do not achieve the same performance level as activated sludge units. Biological oxidation processes are sensitive to temperature and, between 0 °C and 40 °C, the rate of biological reactions increase with temperature. Most surface aerated vessels operate at between 4 °C and 32 °C.

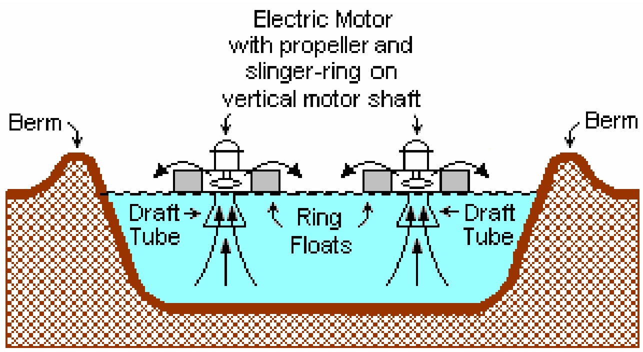


FIG.17. A typical surface-aerated basin

The biological units can be treated as the multiphase flow systems (liquid, solid, gas). In reactors of this type, the appropriate conditions for interphases mass exchange have to be realized. For example, the oxygen has to be transported from gas bubbles to water and consumed by microorganisms together with pollutants. During the process the increasing in the volume and mass of microorganisms (called activated sludge) is observed.

Fig. 18 shows the principles of biological treatment in the aeration tank.

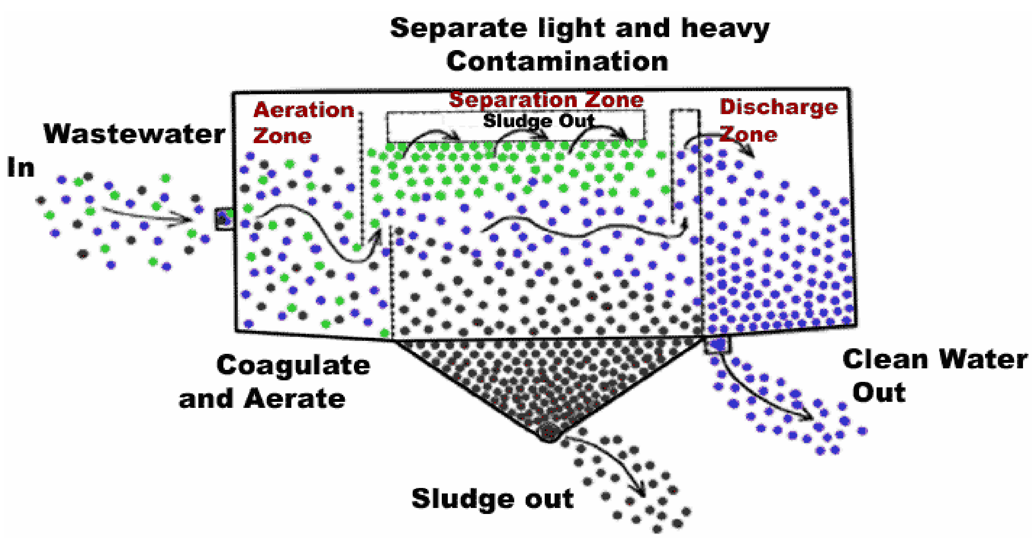


FIG.18. Principle of biological treatment in aeration tank

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.

3.3.2. 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 L-S-G (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.

3.3.3. Secondary clarifier

The wastewater after biological reactors, with sediment contents up to 10 g/l of suspended biomass is directed to secondary clarifiers for sediment removal. The sedimentation process is realized in rectangular settler (with volume ≈ 1000 m^3) or in circular settler (with volume ≈ 2000 m^3), similar in construction to the primary clarifier. The volume of settler has to match with expected wastewater flow rate Q (m^3/h) for secure the sufficient time for sludge particles sedimentation (about 2-3 hours).

In principle the physical processes occurring in secondary and primary clarifiers are the same. In secondary clarifiers only the higher sediment mass is obtained. This mass is much lighter (biomass) as compared to that obtained in primary clarifier (heavy inorganic precipitation).

The wastewater flow structure depends on the geometry of settler:

- construction of water input (overflow, immersed) and output (weirs, overflow),
- location of baffles in settler volume,
- mechanical rotation and parameters of scraper.

The wastewater from the settler output has to be in accordance with the local regulations concerning the quality of discharged water (Biochemical oxygen demand BOD<10 ppm). 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 volume of fluid in settler with residence time shorter than the time necessary for sludge sedimentation. The efficiency of sedimentation process depends on liquid phase flow structure. The proposed flow structure on the base of RTD function can be validated by other independent method i.e. computational fluid dynamics (CFD).

3.4. SLUDGE TREATMENT

3.4.1. Background

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. The sludge is transformed into biosolids using a number of complex treatments such as digestion, thickening, dewatering, drying, and lime stabilisation. 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 degrees Celsius, where these anaerobic micro-organisms thrive without any oxygen.

The stable, solid material remaining, or biosolids, looks, feels and smells like damp earth and makes ideal conditioner for soil. The liquid remaining at the end of the process is usually pumped back into the aeration tanks for further treatment.

Anaerobic digestion is the most common method in use today for treating wastewater sludge. Its attractiveness comes from it being a relatively stable process if properly controlled, with low operating costs and the production of a useful by-product, a combustible gas, which can be used as a source of energy. Anaerobic digestion is a multi-stage biological waste treatment process whereby bacteria, in the absence of oxygen, decompose organic matter to carbon dioxide, methane and water. The end result of the process is a well-established sludge in which 40 to 60% of the volatile solids are destroyed. Finally, a combustible gas consisting of 60 to 75% methane is produced as well.

Because of the large residence times required to synthesize substantial quantity of the gas, the volume of these digesters is in the range of 5000 to 20000 m^3. This is a classical three phase system of large dimensions and hence radiotracers 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.

The digestion process is continuous. Fresh feed sludge must be added continuously or at frequent intervals. The advantages of this process are:

- the organic content of the sludge is significantly reduced by conversion into gaseous end-products; fats and greases are broken down by the process;
- the liquid fraction (supernatant) contains increased levels of ammonia as a result of the breakdown of organic nitrogen (proteins). This makes the digested sludge liquor potentially suitable for agricultural use;
- the biogas that is formed is a mixture of methane (CH_4) and carbon dioxide (CO_2) that can be used for digester heating or to generate power.

The disadvantages of this process are:

- A relatively high initial capital cost is involved, which tends to limit the process to medium to large size WWTP.
- The slow rate of bacterial growth requires long periods of time for start-up, consequently the anaerobic process is considerably slower than the aerobic digestion process. Anaerobic process usually takes several days (15-30 days) as against few hours (12 to 24 hours) needed for the aerobic treatment to achieve equivalent quality of the treated effluent.

3.4.2. Anaerobic biological digester

Anaerobic biological digestion process is known to occur in three sequential steps:

- Break down of complex organic contaminants using extra cellular enzymes synthesized by anaerobic microbes. Since they are carried out by extra cellular enzymes, this step is relatively fast.
- In the second stage the broken down large molecular weight organic contaminants are converted into volatile organic acids such as formic acids, butyric acid, valeric acids etc. by acidogenic bacteria.
- In the third stage, methanogenic bacteria convert these volatile organic acids into methane and carbon dioxide along with a small quantity of hydrogen. This step is known to be the slowest step and hence the rate limiting, deciding the overall digestion times required for anaerobic treatment.

The principle of anaerobic sludge digester is given in Fig. 19.

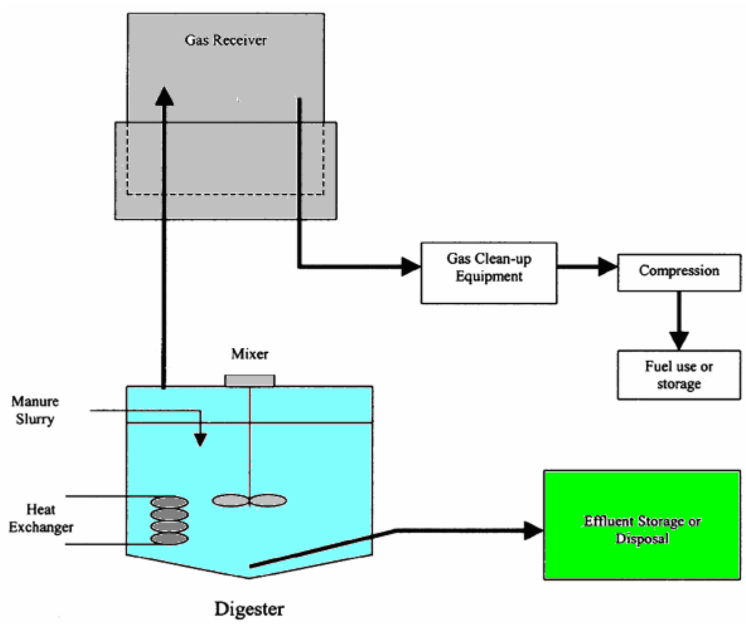


FIG.19. Typical design of an anaerobic sludge digester

The multiphase process inside the digester is a complex one. The fig. 20 presents the schematic of the hydrodynamics developed inside the digester.

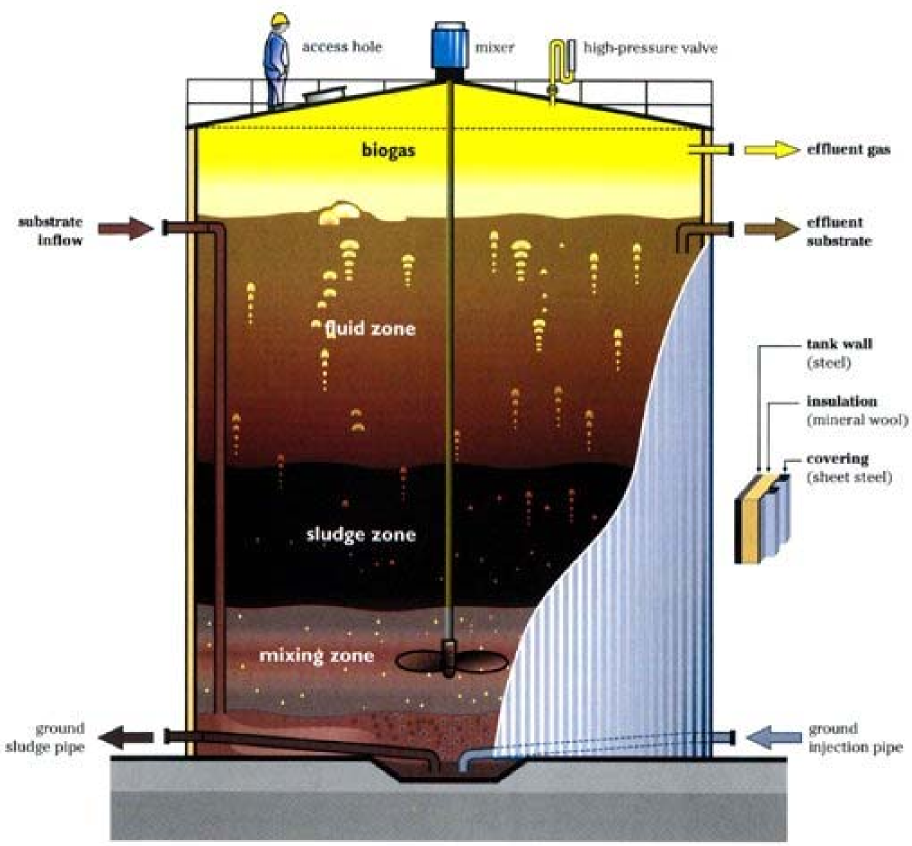


FIG.20. Principle of Anaerobic sludge digester

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. Fig. 21 shows some of these designs.

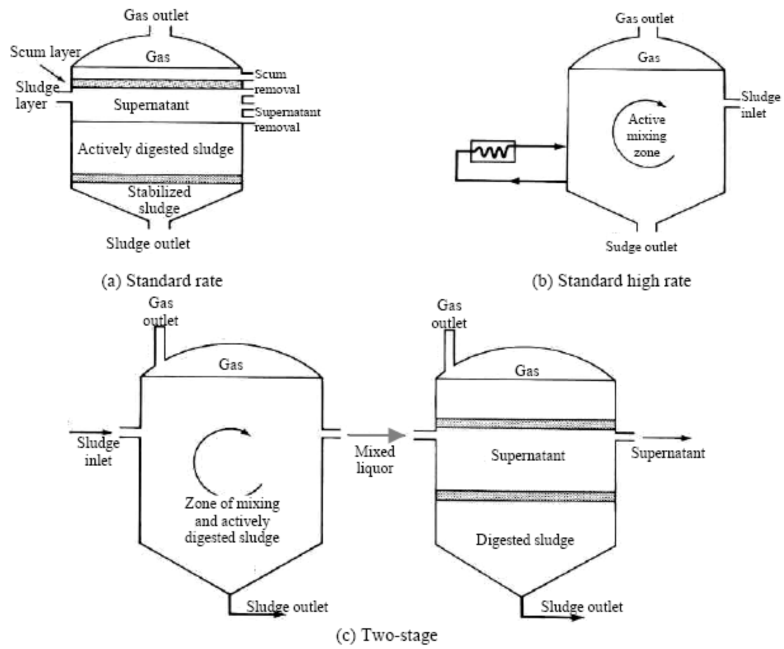


FIG.21. Digester configurations for anaerobic process

3.5. TERTIARY/ADVANCED WASTEWATER TREATMENT

The tertiary treatments are required to obtain treated water of usable quality. Most of WWTPs use disinfection for tertiary treatment to reduce pathogens, which are micro-organisms which can pose a risk to human health. Chlorine is usually dosed into the treated wastewater stream for disinfection. However, UV light can be used to reduce the pathogens. Additional treatment may be required if the treated wastewater is reused for purposes such as irrigation of food crops or where close human contact may result.

Tertiary treatment goes beyond the level of conventional secondary treatment to remove significant amounts of nitrogen, phosphorus, heavy metals, biodegradable organics, bacteria and viruses. In addition to biological nutrient removal processes, unit operations frequently used for this purpose include chemical coagulation, flocculation and sedimentation, followed by filtration and activated carbon. Less frequently used processes include ion exchange and reverse osmosis for specific ion removal or for dissolved solids reduction.

Incineration

If the pollutants are completely bio-refractory or toxic and contain a high concentration of the Total Dissolved Solid (TDS), their incineration is the only option. The effluent after concentration (to about 30 to 50 % of the organic combustible matter) is burned in a combustion chamber or a furnace by mixing it with some fuel such as furnace oil, high speed diesel (HSD), coal powder, etc. The temperature in the combustion chamber is maintained between 900 to 1200 °C, where all the organic pollutants are completely mineralized to CO_2 and H_2O. The hot gases coming out of the furnace are utilized to concentrate the incoming effluent to a desired combustible matter concentration and then are scrubbed with alkali or water to remove minor toxic vaporous compounds.

The scrubbing liquid is also periodically incinerated. Since water has a large heat of vaporization, incineration is very energy intensive and the calorific value of the organic pollutants, if not utilized, is uneconomical. If the organic contaminant load exceeds 5% by weight of the effluent, incineration is self sustainable in terms of energy requirement. Beyond 5% of contaminant incineration can be a net energy generator.

3.6. NATURAL TREATMENT SYSTEMS

WWTPs are complex and costly. There is a possibility to utilize so called “natural systems” for wastewater treatment, which take advantage of the physical, chemical, and biological processes that occur in the natural environment when water, soil, plants, micro-organisms and the atmosphere interact.

Natural treatment systems include lagoons, 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.

3.6.1. What are lagoon systems?

Lagoons are pond-like bodies of water or basins designed to receive, hold, and treat wastewater for a predetermined period of time. If necessary, they are lined with material, such as clay or an artificial liner, to prevent leaks to the groundwater below. 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.

Lagoons must be individually designed to fit a specific site and use. Designs are based on such factors as type of soil, amount of land area available, and climate. An important design consideration for lagoons includes the amount and type of wastewater to be treated and the level of treatment required by regulations. Wastewater leaving a lagoon may require additional treatment, or "polishing," to remove disease-causing organisms or nutrients from the wastewater before it can be returned to the environment.

Dissolved oxygen is present throughout much of the depth of aerobic lagoons. They tend to be much shallower than other lagoons, so sunlight and oxygen from air and wind can better penetrate the wastewater. In general, they are better suited for warm, sunny climates, where they are less likely to freeze.

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.

Wastewater treatment takes place naturally in many aerobic lagoons with the aid of aerobic bacteria and algae. Sometimes, the wastewater in aerobic lagoons needs to be mixed to allow sunlight to reach all of the algae and to keep it from forming a layer that blocks out the air and sun (Fig. 22).

FIG.22. Aerated lagoon system

3.6.2. Advantages and disadvantages of lagoon systems

Advantages:

- Lagoon systems can be cost-effective in areas where land is inexpensive.
- They use less energy than most wastewater treatment methods.
- They are simple to operate and maintain and generally require only part-time staff.
- They are very effective at removing disease-causing organisms (pathogens) from wastewater.
- The effluent from lagoon systems can be suitable for irrigation (where appropriate), because of its high-nutrient and low pathogen content.

Disadvantages:

- Lagoon systems require more land than WWTP.
- They are less efficient in cold climates.
- Odor can become a nuisance during algae blooms and spring thaw in cold climates.
- Unless they are property maintained, lagoons can provide a breeding area for mosquitoes and other insects.
- They are not very effective at removing heavy metals from wastewater.
- Effluent from some types of lagoons contains algae and often requires additional treatment or "polishing" to meet local discharge standard

Lagoons can be round, square, or rectangular with rounded corners. Their length should not exceed three times their width, and their banks should have outside slopes of about three units horizontal to one unit vertical. The bottoms of lagoons should be as flat and level as possible (except around the inlet) to facilitate the continuous flow of the wastewater. Keeping the corners of lagoons rounded also helps to maintain the overall hydraulic pattern in the lagoons and prevents dead spots in the flow, called short-circuiting, which can affect treatment.

3.7. 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 (Fig. 23).

FIG.23. Treated wastewater discharge

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, i.e. the distance where the uniform concentration of pollutants over the width of a water – course 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.

Pollutants introduced into the natural water undergo a gradual degradation – self purification – due to physicochemical processes occurring in aqueous medium and its biological activity. The radiotracer method can be applied to evaluate the kinetics of these degradation processes.

Determination of constant degradation rates of pollutants is based on radioactivity balances made for a radiotracer introduced by impulse wise injection and mass balance for selected substances contained in wastes continuously discharged into a water reservoir.

Solid particles are always discharges with the cleaned wastewater. These particles are support and vectors of the pollutants and their behavior in the environment can be quite different from water behavior. Sedimentation occurs with possible re-suspension and future re-concentration of pollutants in other places and times. Radiotracers are the only tool to study and evaluate such phenomenon.

4. TRACER TECHNIQUES

4.1. PRINCIPLE OF TRACER METHOD

A tracer is any substance whose atomic or molecular, physical, chemical, or biological properties provide for the identification, observation and study of the behavior of various physical, chemical or biological more or less complicated 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 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. 24). 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.

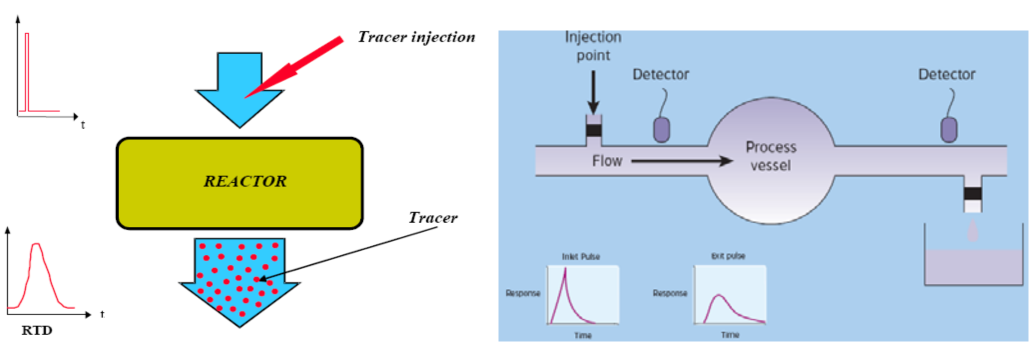


FIG.24. Principle of tracer residence time distribution (RTD)

4.2. RESIDENCE TIME DISTRIBUTION (RTD) MEASUREMENT

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

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

where c(t) is the tracer concentration versus time at the outlet of the system.

The instantaneous injection (Dirac pulse) of tracer is normally applied in practice because 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 whole mean residence time within the system.

The residence time distribution and mean residence time (MRT) are parameters that are extremely pertinent to the operation of chemical reactors, influencing, as they do, both the throughput and the quality of the product. Figure 25 shows an exemplary E(t) function; MRT and its standard deviation (SD) are depicted.

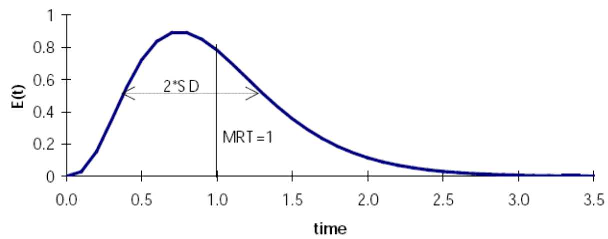


FIG.25. The exemplary E (t) function with MRT and SD parameters shown.

Fig.26 presents E (t) functions having the same MRT values but different SD that is different mixing rates.

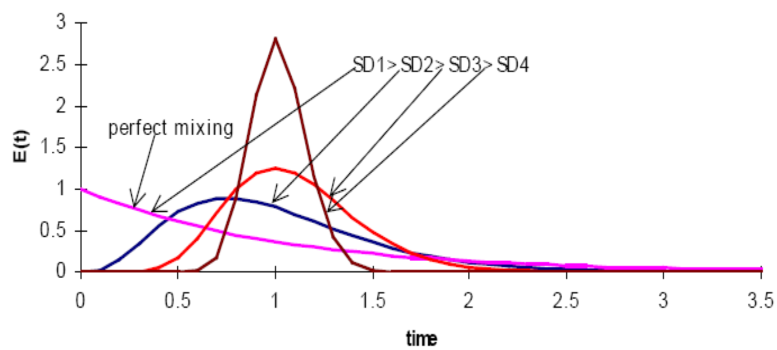


FIG.26. E(t) functions for different degree of backmixing.

4.3. RTD TREATMENT AND MODELING

4.3.1. Calculation of moments

The analysis of the 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 mean residence time and standard deviation. The moments around the origin are defined as:

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

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

The zero[th] moment of the normalized RTD gives the area under the curve, which is equal to unity:

$$M_0 = \int_0^\infty E(t) dt = 1$$

Mean residence time (MRT) is equal to the first moment:

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

The "spread" in the RTD is characterized by standard deviation (σ) or variance (σ^2):

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

where

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

RTDs are often expressed in terms of dimensionless time $\theta = \frac{t}{\bar{t}}$. Thus:

$$E(\theta) = \bar{t}E(\bar{t})$$

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

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

$$\sigma_{cascade}^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots + \sigma_N^2$$

For a constant density fluid flowing in a system of volume V at flow rate Q, the MRT of the fluid (holding time) is theoretically defined as:

$$\tau = V/Q$$

For all normally operating systems, the experimentally measured MRT is the same as the holding time but may differ in case of abnormal performance of the system.

4.3.2. RTD system analysis

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, in the best case, the true RTD of the traced material in a system or in part of a system. Under less favorable circumstances, the experimental curve simply represent an impulse response function between two detection points in the system. This impulse response function does not possess the same conceptual power as a true RTD, but contains valuable information all the same. Appropriate experimental RTD curve is crucial for system analysis or 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 other 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 as close as possible, to the signal from the tracer experiment in the system under study. This approach is sometimes known as system (or systemic) analysis. One therefore needs:

- A set of elementary flow models that describe the basic phenomena of fluid flow,
- A set of rules to combine these elementary models,
- An optimization procedure that makes model response fit with data from the tracer experiment.

It must be emphasized that, apart from these purely mathematical or numerical tools, some amount of intuition, experience and self-criticism is also required to make a sound "systemic analysis" of a tracer experiment.

4.3.3. Ideal models: plug flow and perfect mixer

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 plug flow model is:

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

where δ is the Dirac impulse function.

In case of a perfect mixer (or perfect mixing cell), 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 for the perfect mixer model is:

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

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

4.3.4. Models for non-ideal flows

Real flows often 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. It is often necessary to characterize these effects; convection is related with velocities and flow rates; dispersion has an adverse effect on heat and mass transfer which is important to quantify.

Two types of "dispersed models" can be used for the purpose:

- Axial dispersion model,
- Perfect mixers in series model - also 'called tanks in series' or 'perfect mixing cells in series' model.

1. 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 τ = L/U, where L is the length of the system, and
- Non-dimensional 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. 27). 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).

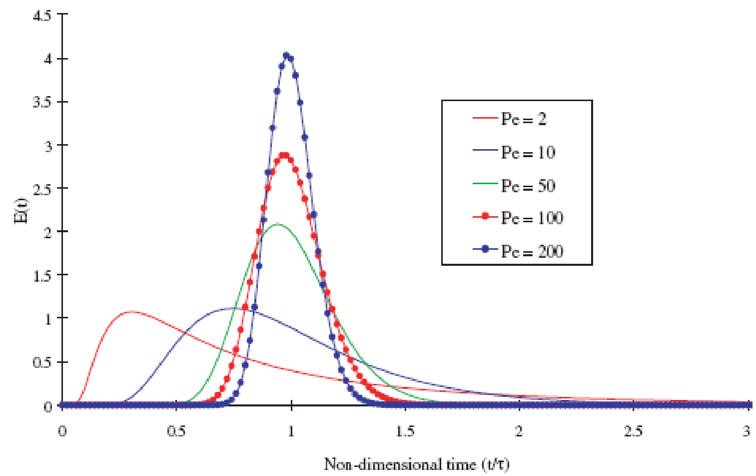


FIG.27. Axially dispersed plug flow model as a function of the Péclet number (P_e).

2. Perfect mixers in series.

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:

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

The effect of varying J is shown in the figure 28.

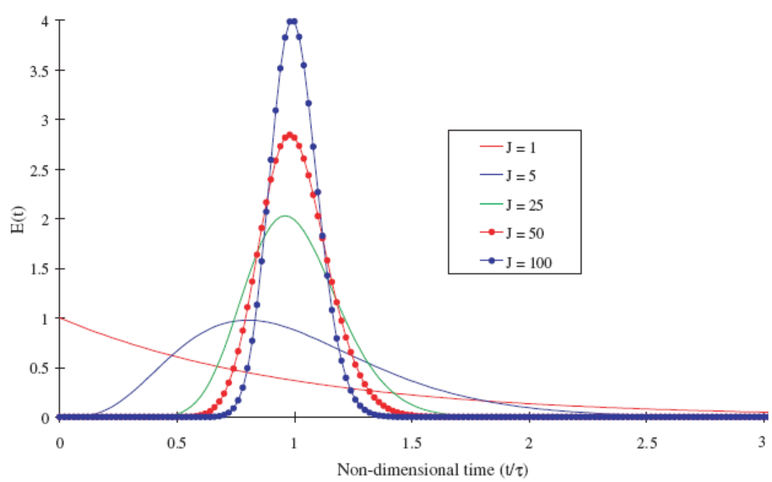


FIG.28. Perfect mixers in series model as a function of J, number of perfect mixers.

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. Differences are insignificant beyond J ≈ 50. The following equivalence relationship is often quoted for large values of J:

$$P_e \approx 2.\ (J-1)$$

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 Pe. 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.

3. Dispersion and exchange models

The "perfect mixers in series with exchange" model is commonly used in RTD applications. The conceptual representation of this model is given in Fig. 29.

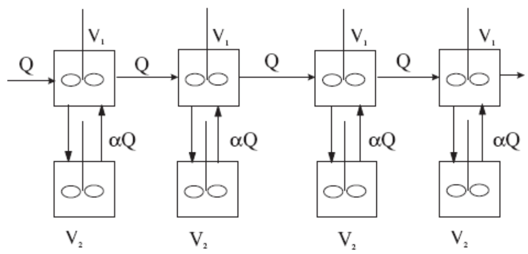


FIG.29. Perfect mixers in series with exchange.

Main flow rate Q goes through a series of J perfect mixers in series of volume V_1; each perfect mixer exchanges flow rate α.Q 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:

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

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 the stagnant zone is expected. An example of a tracer test in a wastewater treatment unit is presented in Figure 30.

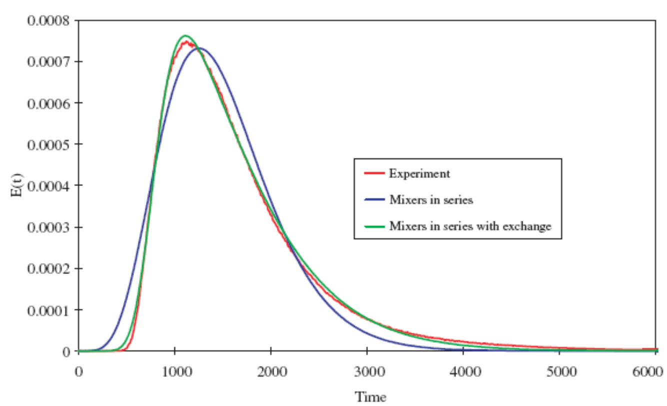


FIG.30. Comparison of mixers in series and mixers in series with exchange model.

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.).

4.3.5. Rules for combining simple 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.

(a) Models in parallel

The pattern is the following (Fig. 31):

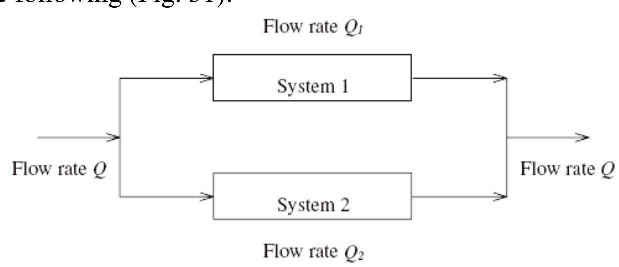


FIG.31. Models in parallel.

(b) Models in series

The pattern is described in Fig. 32.

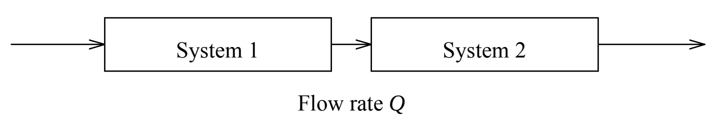


FIG.32. Models in series.

(c) Models with partial recirculation

The pattern is shown in Fig. 33. Part of flow rate (αQ) is recirculating from output into input of the system.

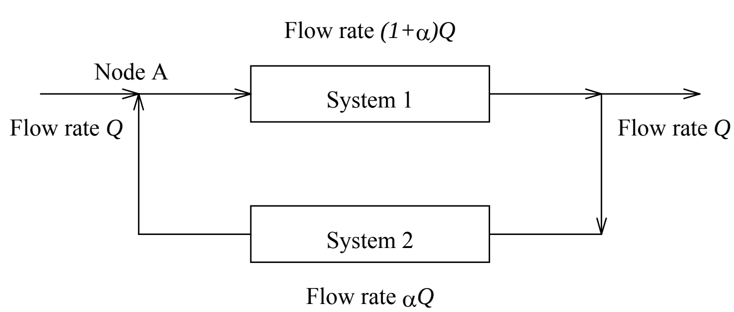


FIG.33. Models with recycling

4.3.6. Optimization procedure - Curve fitting method

Model is a time function with unknown parameters. Modeling means to match to the experimental RTD curve a parametric functional. 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). Simple models (i = 1-2) are preferred as more reliable and practicable.

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

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

There are commercial and homemade RTD software for modeling experimental RTD curve. Progepi RTD software package distributed to many tracer groups allows the user to simulate the response to any input of any network of elementary interconnected basic flow patterns.

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 (combination of perfect mixers, dead volumes, etc.). It happens that different models gives appropriate fitting with the experimental RTD curve. The RTD software may also be used to determine the parameters of the different models giving the same response and, the subsequent physical soundness of these parameters leads to the choice of realistic model. In fact, the results of RTD modeling are not depending on the performance of particular software, but different software facilitates extraction of information and interpretation, in particular for complex process analysis.

There are some guidelines for selecting a model. Table I gives some recommendations of best models for different processes.

TABLE I. RELATIONSHIPS BETWEEN PROCESSES AND EXISTING MODELS DESCRIBING THESE PROCESSES.

Industrial processes	Recommended model
Aeration sludge channel reactor	Perfect mixing cells in series (Number of mixing cells is a function of both gas and liquid flow-rates).
Processes with endless screws (extruders, mixers, spiral classifiers…)	Perfect mixing cells in series exchanging with a dead volume (the number of cells is a function of both inlet flow-rate and speed of rotation)
Multiphase fixed-bed reactors : RTD of liquid phase	Two perfect mixing cells in series model in parallel
Classified bed crystallizers	Perfect mixing cells in series with back-mixing

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.

4.4. RTD 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.

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.

Experience has shown that two common phenomena happening in any kind of reactors are short circuiting (bypass) stream and dead volume (Fig. 34). A short circuiting stream is characterized with a low residence time within the tank. Dead volumes are stagnant water or scaled zones that are not active in the process. Dead zones reduce the effective (active) volume, as a consequence, the process efficiency is smaller that expected.

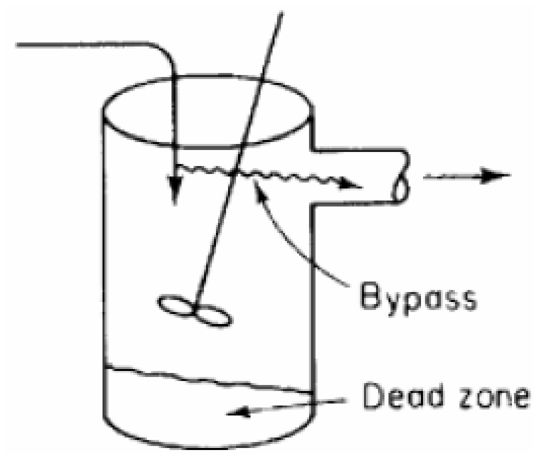


FIG.34. Illustration of a tank reactor with short circuiting stream (bypass) and with dead zone.

4.4.1. Dead/stagnant volume

Looking more closely at the continuously stirred tank, it is possible to determine what fraction of the tank is 'active'. The theoretical mean residence time, τ, of fluid entering a perfectly mixed tank is given by the equation $\tau = V/Q$, where V is the tank volume (as designed) and Q is the volumetric flow rate (as measured during the tracer test). However, the real mean residence time can be experimentally determined from the measured RTD curve.

Usually for a perfectly mixed system the counting rate should return to zero after 2 or 3 mean residence times. 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. Instead, it will exhibit a long tail that indicates the slow exchange of flow between the active and stagnant volume.

The dead volume normally is considered as blocked zone where tracer 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 the active volume, V_a, is V_a=V- V_d , where V_d is the dead space or volume

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

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 importance. 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; (iv) the so called “dead volume” in fact is “stagnant volume” that means it exchanges flow very slow and causes the long tail in the experimental RTD curve.

4.4.2. Bypassing / 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 two peak areas gives the percentage of the channeling effect (or bypass transport), and usually it is less than 10-15%.

The amount of bypassing could be easy 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 that the main flow peak.

4.5. INTEGRATION OF RTD TRACING WITH CFD SIMULATION

4.5.1. Computational fluid dynamics method

At present, two methods are generally used for investigation of industrial complex processes (WWTP included), tracer residence time distribution (RTD) experimental technique (systemic or global analysis), and computational fluid dynamics (CFD) simulation.

The concept of the residence time distribution (RTD) is fundamental to any reactor design. RTD for process equipment is typically measured using stimulus-response tracer experiment to detect design flows such as bypass, channeling and dead zones. The real time experimental RTD tracing is simple and reliable; it provides various important hydrodynamic parameters 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 (combination of perfect mixers, dead volumes, etc.).

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 is a fine and predictive analysis, which 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. CFD simulation can be extrapolated to other flow conditions once it is validated. 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. The RTD-CFD interaction is both sides. The CFD can be used also to complement the information obtained from the RTD systemic approach.

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. In fact, these two approaches, experimental and numerical, are complementary to each other. The RTD systemic approach detects and characterizes main features of the flow (mixing and recirculation) 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 with complex multiple feed tube geometry has been used to measure the RTD as a function of flow rate. The vessel is driven by a Rushton impeller and is either baffled or not baffled for the different cases studied (Fig. 35). At both ideal and non-ideal conditions, experiments and simulations of the RTD have been performed.

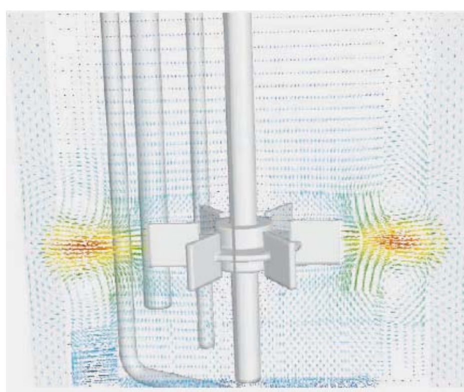


FIG.35. Fluid flow simulation of a 1.4 liter baffled stirred tank operating with a Rushton impeller

For the CFD work, there are multiple approaches for predicting RTD. In one approach, the tracer fluid is represented by a large number of discrete particles and Lagrangian particle tracking analysis is done with the discrete phase model (DPM). A histogram of time at the outlet is the RTD. One drawback of this method, however, is that a large number of particles are required to ensure proper statistics. Alternatively, the tracer fluid can be treated as a continuum by solving a transport equation for the tracer species. It is the latter continuum approach that has been used for the crystallization project. A single-species flow field was first obtained using the k-ε turbulence model.

A passive tracer was then introduced with a step change in its concentration in the feed. The tracer was modeled using a user-defined scalar transport equation. The surface-area averaged tracer concentration was monitored as a function of time at the outlet. The results provided the exit age distribution of the tracer in the reactor, and therefore, represent the RTD. The FLUENT predictions were found to be in excellent agreement with the experiment over a broad range of flow rates and impeller RPM values, for both baffled and non-baffled tanks (Fig.36).

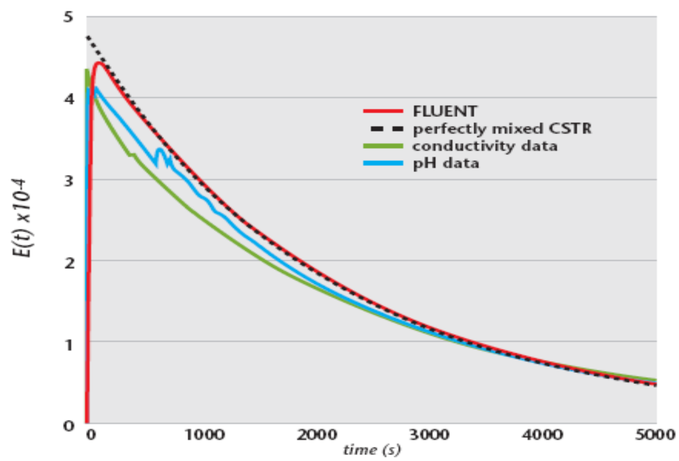


FIG.36. Comparison of experimental and calculated RTD function, E(t)

Since RTD are routinely and rather easily measured for process equipment, the RTD predictions allow a rather painless way to validate a complex flow simulation. In addition, with the aid of CFD simulations, process scale-up can be facilitated without expensive work on an intermediate scale in a pilot plant. The question of whether to construct a pilot plant or not depends on whether engineers are in control of all the major variables for the process. Using FLUENT (FLUENT CFD software package is mostly used) a small-scale reactor can be modeled to accurately predict its residence time distribution. Various potential large-scale reactor designs can also be modeled in the same manner, and the residence times predicted to verify that upon scale-up, the large-scale reactor controls the major variables for the process in the same way that the small-scale reactor does.

4.5.2. CFD simulation of WWTP's units

CFD-RTD combined method is largely used in investigation of WWTP (Fig. 37). CFD is used 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.

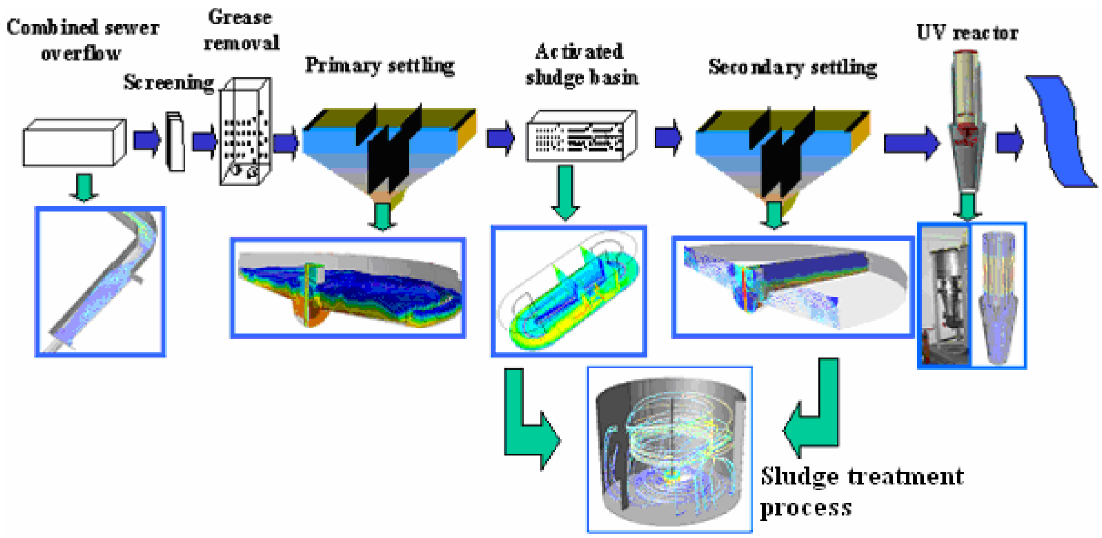


FIG.37. Example of the CFD modelling of the WWTP's units

4.5.3. The advantages of using CFD

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 CFD, 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.

4.6. NEED FOR TRACER INVESTIGATIONS IN WWTP

Tracing technology allows movement of water mass, sludge and contaminants (whether dissolved or particulate) to be measured in a range of water and 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 using multiple tracers.
- 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 maintenance 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 Computational Fluid Dynamics (CFD) models.

4.7. ECONOMIC BENEFITS OF TRACERS UTILIZATION IN WWTP

It is quantitatively difficult to assess the economic benefit of the use of radiotracers in WWTP unlike in multiphase reactors 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 us in achieving the same.

In developing and developed 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 ponds more effectively,
- providing data for the design of future ponds.

4.8. CONVENTIONAL TRACERS

Different types of conventional tracers exist. Table II presents non-radioactive tracers.

TABLE II. NON-RADIOACTIVE TRACERS

Tracer	Description
Color tracer for fluids	The detected parameter is the color of the tracer which is measured through a light or laser beam. The wavelength has to be adapted to the fluid in order not to be absorbed in it.
Fluorescent tracers for fluids	The tracer is excited by a light or laser beam, mainly operating in the UV region. Characteristic fluorescent radiation with a higher wavelength is emitted by the tracer and detected with a photodiode detector
Chemical tracers for fluids	Chemical tracer is any easily detectable substance (gas, liquid or solid) measurable at very low concentrations by instrumental analytical techniques such as gas chromatography (GC or GC/MS), high-performance liquid chromatography (HPLC), inductively coupled plasma spectroscopy (ICP/MS), neutron activation analysis etc.

The major non-radioactive tracers used for investigation of WWTP's units are:

Chemical tracers. Their analysis is made by chemical methods generally off line (by sampling), sometimes on line.

This category of tracers offers a wide range of possibilities of which reasons they have been actively used in hydrology and environment (sodium dichromate, sodium iodide, sodium chloride, sodium nitrite, lithium chloride, potassium chloride and manganese sulphate). Sulphur hexafluoride (SF_6) measured by gas chromatography is an example of a chemical tracer used in air pollution studies. Chemical tracers are not suited to most of the industrial applications. In wastewater treatment units they are convenient only for water tracing.

Optical tracers. They can be divided in two categories, color tracers and fluorescent tracer. These tracers are organic substances, for example, uranine, rhodamine B, sulforhodamine B, sulforhodamine G, rhodamine WT, eosine, etc. These tracers can not be used in wastewater applications because they require at least transparent walls and transparent fluid.

4.8.1. Fluorescent tracer studies

Fluorescent tracer studies are reported using Turner Designs 10-AU Fluorometer and Rhodamine WT for on-line investigation of water phase dynamics in some WWTP units. Fluorometer model 10-AU can detect as low as 10 parts per trillion (0.01µg/L) of Rhodamine WT in potable water, and 100 parts per trillion (0.1µg/L) in industrial and sanitary sewage.

The fluorescent studies in WWTP were focused in the following processes:

- Calibrate Flowmeters: Flow measurement by dye dilution is chosen for its superior accuracy (+/- 2%). Flow metering devices typically have measurement errors of +/- 20% when installed in the field- check the accuracy of these devices.
- Verify flow capacity: Wastewater treatment plants use flow measurement by dye dilution to determine if they are operating at their hydraulic limit. Discovering an additional 25% capacity through accurate flow measurement has prevented treatment plants from spending millions $ to increase capacity.
- Measure pump performance: Power plants and wastewater treatment facilities use dye tracer systems to accurately measure flow in and out of pumps, turbines, condensers, and other flow system equipment; and to troubleshoot, check the performance of, and measure the efficiency of such equipment.
- Mixing zone studies: Engineering consulting firms use fluorescent tracers to determine how quickly a wastewater stream mixes with another body of water. The tracer mimics the behavior of the discharged wastewater. Mixing zone studies are conducted when new plants are built and discharge permits are granted.
- Tank retention time: Tracers are used to measure the time that a given volume of water is retained in a tank. This study is conducted by wastewater treatment plants in order to determine the efficiency of settling tanks and chlorine contact chambers.

4.8.2. Chemical tracer LiCl a good tracer for water phase

Tracer tests using lithium chloride (LiCl) solution to trace water phase in different WWTP units are reported in many countries. As chemical LiCl has the following advantages:

- It is a conservative tracer, that means does not react or degrade in wastewater,
- It has a low detection and measurement limit,
- It has no toxicity,
- It has a very low natural concentration in drinking water and urban waste water.

The common way of analysis is using atomic absorption spectrometry in the flame.

4.9. LIMITATIONS OF CONVENTIONAL TRACERS IN WWTP INVESTIGATIONS

The conventional tracers, which are used in the chemical industry where the gaseous, liquids and solid movements are to be monitored, are the following.

For gas phase analysis, i.e. flow rate, concentration and the residence time distribution, reactive gases such as chlorine, SO_2, and oxides of nitrogen are used. 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.

Many a times the gas flow rates in the case of wastewater treatment 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. Similarly for liquid phase, the traces used are colored dyes (rhodamine, fluoroscene), conducting liquids (electrolyte solutions) or acids and alkalis to measure the color intensity, conductivity or the pH of the liquid to be analyzed for flow, residence time or mixing respectively. In the case of the wastewater treatment schemes these can not be used at all, as many a time the wastewater itself is heavily colored and hence the dye 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 the 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 (TDS) 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.

All the above discussion clearly indicate a requirement of a class of the tracers which does not necessarily require sampling, can be analyzed on-line and will analyze the entire quantity of all the three phases simultaneously for their dynamic and time dependent variation. Radiotracers offer a complete solution to these typical problems as we have seen in the variety of the case studies discussed in the report.

Table III gives a summary of these findings and specific recommendations for the analysis of the various units in WWTP and the appropriate radiotracers for the same:

TABLE III. SUMMARY OF RADIOTRACERS AND THEIR UTILITY IN WWTP OPERATIONS

1) Gas

Non-nuclear techniques	Radiotracers
Traces Used: Reactive Gases	Recommended Non-Reactive Radiotracers
Cl_2, SO_2, NO_2, SF_6, etc.	Ar-41, Kr-79, Br-82 (as CH_3Br)
Advantages	
- Easy availability - Simple analysis	- High selectivity - Low detection limit - In-situ/On-line measurement (no sampling needed)
Disadvantages	
- Poor selectivity - Poor detection threshold - Statistically representative sample	- Availability - Costs - Radiation safety regulations
Field of applications in WWTP: (1) Aeration tanks, (2) Biological filters, (3) Disinfection unit, (4) Anaerobic digester	

2) Liquids

Non-nuclear techniques	Radiotracers
Tracers used	Radiotracers recommended
Electrolytes (NaCl solution) - conductivity Dyes (Rhodamine, Fluorescence) - color Acids & Alkali – pH	KBr, NH_3Br, Tc, In-EDTA, Sc, I, Na_2CO_3
Advantages	
- 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
Disadvantages	
- Not suitable for color, conducting liquids (usually in WWTP) - Stratification possibility due to density difference - Large threshold detection concentration - Possible interference with WWTP treatment operation	- Radiation safety regulation - Relatively expensive detection equipment
Field of applications in WWTP: (1) Central collection/Flow rates, (2) Equalization tank, (3) Flash mixer, (4) Clarifiers, (5) Aeration vessel (ASP), (6) Anaerobic digesters, (7) Dispersion of discharge in water	

3) Solids

Non-nuclear techniques	Radiotracers
Tracers used	Radiotracers recommended
No known solid tracers Current method: sampling, filtering, drying, weighing	In-113m, Tc-99m, Au-198, etc.
Advantages	
-	- Same as in case of liquid phase radiotracers - Can be independently detected without interference with gas and liquid detection
Disadvantages	
- Tedious - Statistically representative sampling	- Radiation safety regulation - Relatively expensive detection equipment
Field of applications in WWTP: (1) Collection networks, (2) Sand and grit removal, (3) Clarifiers, (4) Biological reactors (aerobic and anaerobic) (5) Discharge networks	

Limitations of conventional tracers can be summarized as follows:

Gas phase: reactive gases such as chlorine, SO_2, and oxides of nitrogen
There is always a problem of getting a statistically representative sample.

Liquid phase: colored dyes (Rhodamine, fluorescence), conducting liquids (electrolyte solutions) or acids and alkalis. These can not be used at all, wastewater itself is heavily colored; dyes are also photosensitive reducing intensity when exposed to sunlight for extended periods; effluent are highly conductive.

Solid phase: standard procedure is to collect solid samples, dry and weigh them.
Wastewater contains a variety of solids differing widely in density and concentration and hence collecting a statistically representative sample is difficult if not impossible.

Radiotracers only can offer a complete solution to many problems. Radiotracer advantages are:

- Radiotracer method is ideal for assessing proper functioning, optimization and 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 case of solids transport in clarifiers and digesters, radiotracers are the only tracer option.
- 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.
- Use of radiotracers in WWTP should be promoted vigorously to reduce the adverse environmental impact of the improperly treated wastewater discharge.

5. RADIOTRACER TECHNIQUES

The methodology is basically the same as described above for tracers in general (RTD approach). The main particularity of these tracers is their gamma radiation emission. Most of the radiotracer applications in industrial reactors make use of artificially produced radionuclides. 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. They offer possibility of in-situ measurements, providing information in the shortest possible time. 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. The emission of radiation is a specific property of the radionuclide, not affected by interference from other materials in the system. In a single-phase system, knowledge of the RTD allows us to predict exactly the performance of that system. The extension of RTD theory to multiphase systems is now being researched in many chemical engineering laboratories.

5.1. SELECTION OF RADIOTRACERS

5.1.1. Type of radiotracers

Selection of a suitable radiotracer is very important for the success of the leak detection test. Radiotracers may be classified in categories according to their intended use. They may further be classified into tracer types according to their intrinsic properties. There are several ways whereby this can be done. Definitions of passive and active tracers may be as follows:

- ***Passive or conservative*** tracers: The requirement is that the tracer shall passively follow the phase (gas, liquid, solid) or phase fraction into which it is injected (or introduced) without any chemical or physical behavior different from that of the traced component itself. In addition, the tracer must not perturb the behavior of the traced phase in any way, -neither must the fluid phase or its components perturb the tracer behavior.

- ***Active or reacting*** tracers: The tracer is taking active part in the process in qualitatively predictable ways, and is used to measure a property of the system in which it is introduced. The degree of the active part-taking is a quantitative measure of the property to be determined.

Factors that are important in the selection of a radiotracer are given as follows:

- Physical/chemical form and properties of tracer with respect to the system under investigation
- Half-life of tracer
- Specific activity of tracer
- Type and energy of radiation emitted regarding detection geometry (walls nature and thickness)
- Availability and cost of tracer
- Method of measurement (sampling or in-situ measurement)
- Handling of radioactive materials, radiological protection/regulations.

Under certain circumstances, tracer has to be chemically identical with the traced substance and then one has to use an intrinsic tracer (also called 'chemical radiotracer'). This is the case when studying chemical reaction kinetics, solubility, vapor pressures, processes dominated by atomic and molecular diffusion, etc. Radioactive isotopes of the traced elements and labeled molecules are used as intrinsic tracers, for example, $^{1}H^{3}HO$ for water, $^{24}NaOH$ for NaOH or $^{14}CO_2$ for CO_2, etc.

Whenever the chemical identity of the tracer with the material it follows is not required the tracer has merely to fulfill a limited number of not very rigid physical and physiochemical conditions. This type of tracer is commonly referred to as an extrinsic (or physical) radiotracer. The majority of tracer techniques applied in WWTP units make use of these extrinsic radiotracers. 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 the many radiotracers that have been successfully used in aqueous solutions are ^{51}Cr-EDTA complex, ^{113m}In-EDTA complex, $Na^{131}I$, $K^{131}I$, $^{24}Na_2\,CO_3$, $^{24}NaHCO_3$, $NH_4\,^{82}Br$, $H^{198}AuCl_4$ and pertechnetate, $^{99m}TcO_4^-$.

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, methyl bromide ($CH_3{}^{82}Br$) and ^{133}Xe.

Surface labelled sand and silt with ^{198}Au, ^{113m}In, ^{51}Cr, $^{175+181}Hf$ or ^{46}Sc have been widely used in sediment transport studies in WWTP. Specially produced glasses containing a chemical element that can be activated by (n, γ) reactions, are available to any given size distribution and are used very extensively as sand tracers. ^{198}Au, ^{51}Cr, ^{192}Ir and ^{46}Sc are the radioactive nuclides often induced.

5.1.2. 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 tracer leak detection mostly in liquid phase: Mo-Tc-99m, Sn-In-113m, Cs-Ba-137. Only Mo-Tc-99m, which is largely used in nuclear medicine, is available in the market with reasonable price. It has rather limited applications due to short life and low gamma energy.

Sn-In-113m 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 leak detection. It has longer life and larger gamma energy in comparison with Tc-99m, but is two-three times more expensive.

Cs-Ba-137 generator produces very short live radiotracer but has practically very long life (several years at least). This is a very useful radiotracer generator for routine service to end users, in particular for liquid flow rate measurement and leak detection in processing plants, because of its high gamma energy which can be easily detected from outside pipes, and of its safety. The Cs-Ba-137 generator is not available in the market. There are some tracer companies that produce home-made Cs-Ba-137 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, injected activity ≈ 4 to18 GBq,
- ^{99m}Tc in reduced $SnCl_2$ medium: Sludge labelling-tracing in wastewater treatment plants for RTD measurements, injected activity ≈ 4 to 18 GBq,
- ^{113m}In in chloride solution: Sludge labelling-tracing in wastewater treatment plants for RTD measurements, injected activity ≈ 3.7 GBq,
- ^{113m}In in EDTA complex: Water tracing in various hydraulic pilot plants and laboratory facilities, injected activity ≈ 0.37 to 3.7 GBq,

5.1.3. Estimation of amount of radiotracer

After selecting a suitable radiotracer for a particular application, the amount of tracer required to be used is the second important step in designing a radiotracer experiment. The lower limit of the amount of tracer is estimated according to measurement sensitivity, accuracy desired, dilution between injection and detection points, background radiation level *etc.* However, the upper limit is set by radiological safety considerations. The amount of radiotracer required for a leak detection test depends on the following factors:

- Accuracy
- Efficiency of measurement or calibration factor of detection system
- Expected level of dilution/dispersion
- Half life of radiotracer used
- Background radiation level
- Mode of injection and detection.

Accuracy is given by the standard deviation of the intensity of radiation. In field work an accuracy of 5-10 % is acceptable. Efficiency of radiation detection is expressed in counts per second per specific activity unit cps/μCi/m^3 (or: counts x s^{-1} x Bq^{-1} x m^3). The efficiency of detection depends upon the following factors:

- Geometrical factor
- Intrinsic efficiency of the detector
- Absorption coefficient of material between the source and detector.

Scintillation detectors NaI(Tl) are commonly used for radiotracer applications because of their high efficiency for gamma ray detection. The intrinsic efficiency a 1"x1" NaI(Tl) detector for 100 keV, 500 keV and 1 MeV energy photon is about 39%, 26%, 10% respectively. For NaI(Tl) 2"x2", which are commonly used in field tests, the intrinsic efficiency is almost four times higher than for 1".

The background radiation (cosmic radiation and natural radioisotopes) level is required to be known prior to the tracer test for the estimation of the amount of activity required. In general the radiotracer concentration *(*maximum count rate coming from the radiotracer only) should be at least 5-10 times the background radiation level at the measuring points. However, high accuracy demands that maximum count rate could be about 100 times that of the background radiation level. The losses due to splitting of tracer stream, adsorption, evaporation *etc.,* should be taken into consideration while estimating the amount of activity for a particular radiotracer experiment (these effects are known from the plant engineers).

An empirical simple way to calculate radiotracer activity for a leak test is to consider radiotracer completely homogenized in total volume of the pipe or vessel. In this case, A activity distributed uniformly in V volume of the pipe provides a specific activity of A/V (Bq/m^3). The sensitivity k of the detection system is normally known from the laboratory (laboratory calibration imitating process conditions in bench model gives the correspondence between count rate I, cps and activity A, Bq/m^3). Radiation intensity I, cps that gives an acceptable accuracy is also known (5-10 times more than the radiation background intensity I_b). In this case the activity is calculated simply by relation:

$$A\ (Bq) = V\ (m^3)\ .\ I\ (cps)\ .k\ ((Bq/m^3)/cps)$$

This simple approach gives much higher estimation of radiotracer needed for a test because it considers the tracer uniformly distributed in the whole volume of pipe or vessel, that is not the case, tracer is moving as a dispersed cloud occupying only a limited volume of the vessel. Normally the half of this calculated activity is taken in practice because tracer is moving in peak form cloud where the concentration in the peak wave is several times more that calculated.

5.1.4. Tracer injection system

Most of radiotracer employed in WWTP processes are gamma emitters and special care needs to be taken in order to prevent unexpected radiation exposure of practitioners. The requirement for proper injection system could be summarized as follows;

- Minimize radiation exposure and contamination,
- Instantaneous discharge of radiotracer into a process system
- Easy installation.

The above requirements can be achieved by taking the following issues into account:

- Compact design with heavy material in order to shield radiation
- Secure distance from radiotracer by remote operation for injection procedure
- Making the system adaptable to a radiotracer container
- Operation with strong drive force such as pressure to push radiotracer out of an injector in extremely short time.

Injection of tracer into the vessel is performed by special injectors designed for liquid, solid or gas flows under different pressures (Fig.38).

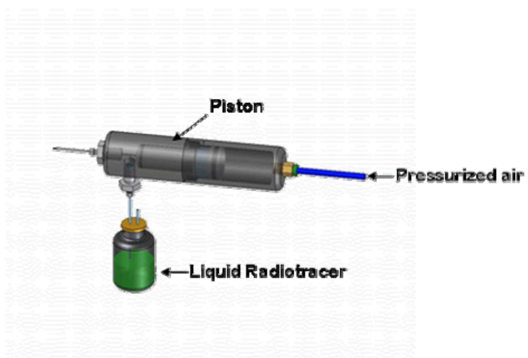


FIG.38. Liquid tracer injector(left shielded syringe, right on site with gas bomb)

A particular case occurs for sludge particles which have to be labeled and injected more or less simultaneously with a minimum action on them in order to warranty that their physico-chemical behavior is not modified by the labeling operation (Fig. 39).

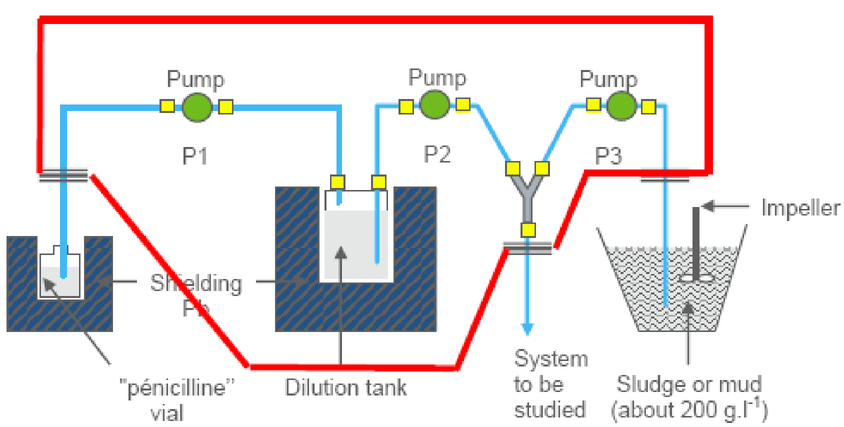


FIG.39. Scheme of a labelling / injection unit for sludge particles

5.2. RADIOTRACER MEASUREMENT

5.2.1. 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''x 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.

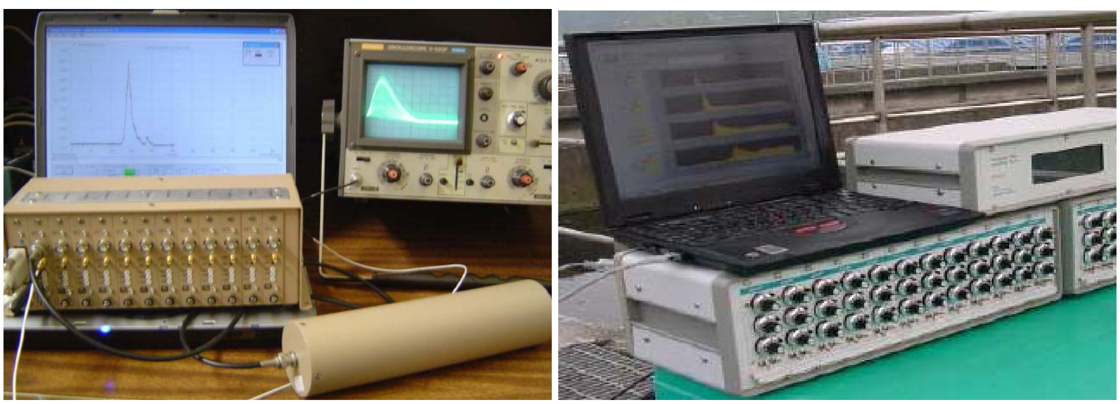


FIG.40. Data acquisition systems for online radiotracer tests

The data acquisition system, which collects signals from several radiation detectors, is the basic equipment for online radiotracer RTD measurements (Fig. 40). 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''x 1'' NaI (Tl) scintillation detector for ^{82}Br measured in water with an infinite detection geometry condition gives 65 cpm/kBq/m^3.

The probes are placed (Fig. 41):

- 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.

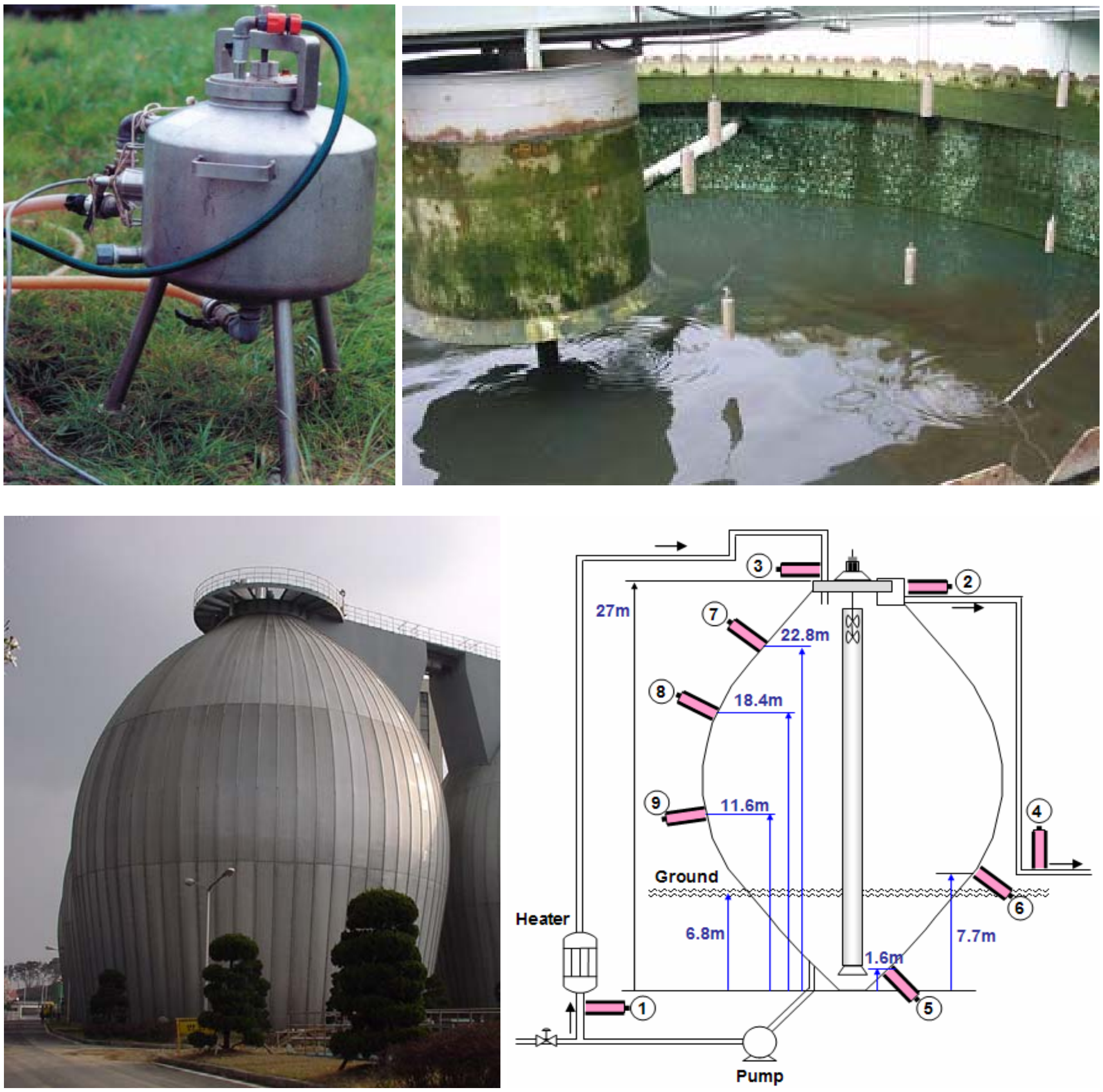


FIG.41. Examples of detection probe locations: inside the detection chamber; immerged in wastewater; on an anaerobic digester (9 probes placed at the inlet, at the outlet and around the system)

5.2.2. Units of radiation activity and dose

Curie (Ci) is old long-used unit of radioactivity. It has been replaced with the SI unit, the Becquerel (1 Bq = 1 disintegration per second):

$$1 \text{ Ci} = 3{,}7.\ 10^{10} \text{ Bq}$$

The Curie is a large amount of radioactivity while the Becquerel is a very small amount. For convenience, milli- (1 thousandth) and micro- (1 millionth) Curies or Mega- (million) and Giga (billion) Becquerel's are used in everyday practice.

Dose is a generic term that means absorbed dose, dose equivalent, effective dose equivalent, committed dose equivalent or total effective dose equivalent. Each of these is defined below:

Absorbed dose: It is the energy imparted by ionizing radiation per unit mass of irradiated material, and its measurement unit is the Gray (Gy). Gray is defined as a unit of energy absorbed from ionizing radiation, equal to 10 000 ergs per gram or 1 joule per kilogram of irradiated material. The unit Gray can be used for any type of radiation; it does not describe the biological effects of the different radiations. The old unit of absorbed dose is “rad”. New and old units are relation is: 1 Gray (Gy) = 100 rads.

Equivalent dose: This relates the absorbed dose in human tissue to the effective biological damage of the radiation. It is a multiplication of (absorbed dose) x (quality factor) x (other necessary modifying factors of interest). The Sievert (Sv) is a unit used to derive the "equivalent dose". Normally, the equivalent dose is expressed in milliSieverts (mSv).

Not all radiations have the same biological effect, even for the same amount of absorbed dose. Equivalent dose is calculated by multiplying absorbed dose (Gy) by a quality factor (QF) that is unique to the type of incident radiation.

Roentgen (R): The roentgen is an old unit used to measure a quantity called "exposure." This unit is used only for gamma and X rays < of energy less then 3.5 MeV and only applies in air. One roentgen is equivalent to depositing 2.58×10^{-4} coulombs per kg of dry air. It is a measure of the ionizations of the molecules in a mass of air. The main advantage of the Roentgen is that it is easily measured directly.

There is an empirical relation between the radiation dose rate in air (exposure in R/h) and the activity A (Ci) of a point source of gamma rays in a distance r (m):

$$P = \Gamma \,.\, A/r^2$$

where: dose rate factor Γ is an empirical factor for the specific radioisotope that includes absorption, geometry, photon per disintegration, energy, and all other factors that affect the dose rate from the radioisotope at unit distance. The inverse-square law of gamma absorption in air is assumed as long as the source can be considered a point source. The absorption of gamma rays in air is also assumed to be negligible. This empirical relation is used in field radiotracer work as a simple approach for rough calibration of radiation detectors. Dose rate factors are given in R/h for 1 Ci at 1 m. Γ factors are usually tabulated for activity of 1 Ci and distance of 1 m. For example, ^{60}Co has the dose rate factor of 1.35, ^{137}Cs of 0.30, and ^{198}Au of 0.23.

5.2.3. Radiation safety considerations

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

Figure 42 shows different types of radiation and their penetration in the matter. For gamma rays mostly employed in on-line radiotracer tests the most commonly used material for shielding is lead.

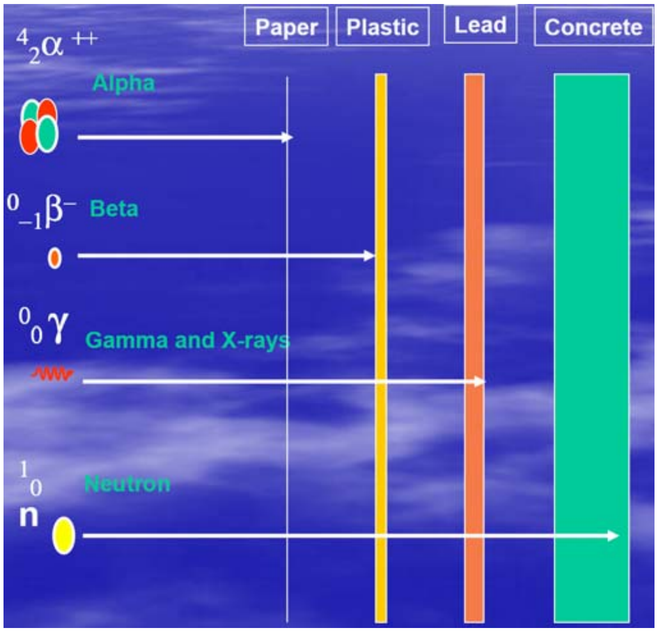


FIG.42. Shielding for various type of radiation

5.2.4. Water tracers for hydraulic characterization

Tritiated water (HTO) is the only intrinsic radiotracer for water. One has to use it very carefully due to possible interfering exchange of ^{3}H (T) with hydrogen in other molecules, evaporation, or exchange with atmospheric moisture. Measurement of ^{3}H requires sampling and laboratory measurements by liquid scintillation. Other tracers, gamma emitters, most commonly used in aqueous solutions are listed in Table IV:

TABLE IV. SOME WATER TRACERS

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
Activity	37 to 7400 MBq		37 MBq to 37 GBq	37 to 7400 MBq		
Obtention	Generator ^{137}Cs – ^{137m}Ba	Generator ^{113}Sn – ^{113m}In	Generator ^{99}Mo – ^{99m}Tc	Reactor activation		
Preparation	None	EDTA complexation	None	Ammonium bromide	KI or NaI	EDTA complexation

5.2.5. For solid movement characterization

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 V and VI present some radiotracers for labeling different kind of sludges, in particular for fine particle silt and inert particle sand.

TABLE V. SOME TRACERS FOR FINE PARTICLE SLUDGE (SILT)

Isotope	^{113m}In	^{99m}Tc	^{82}Br	^{198}Au	$^{181+175}Hf$	^{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		900 and 1100
Activity	37 to 7400 MBq	37 MBq to 37 GBq	37 to 7400 MBq	37 MBq to 7400 MBq			
Obtention	Generator ^{113}Sn – ^{113m}In	Generator ^{99}Mo – ^{99m}Tc	Reactor activation				
Preparation	None	Reduction by $SnCl_2$	Chloride solution				

TABLE VI. SOME TRACERS 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
Activity	37 MBq to 18 GBq				
Obtention	Reactor activation				
Preparation	Glass powder				

5.2.6. For gas movement characterization

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

TABLE VII. SOME GAS TRACERS

Isotope	^{41}Ar	^{76}As	^{82}Br	79Kr
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
Obtention	Reactor activation			

6. 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.

6.1. RADIOTRACER APPLICATIONS IN WWTP IN POLAND

6.1.1. Introduction

Three major units involved in wastewater treatment process in Polish petrochemical industry are equalizer-clarifier, biological aeration chamber with settler and final sedimentation basin. The effectiveness of purification process carried out in such installation strongly depends on flow pattern of wastewater and sediment. From the process engineering point of view these tanks represent the continuous multiphase flow system. In equalizer and settlers the concurrent flow of water and sediment occurs. In biological reactor three phases flow-water, sediment, air - exists and it is very important to realize their good contact and conditions for interphase oxygen transport.

The experience has indicated that the best radiotracer for liquid phase is Br-82 - in form of aqueous KBr solution; in some cases the dye tracers Rhodamine-B or Fluoresceine have been applied as well. The sediment is labelled by La-140 radioisotope - in $La(NO_3)_3$ form, firmly absorbed on the sediment surface.

The multipoint mobile radiotracer laboratory has been set up for field investigations. The system allows registration of signals from 16 different independent measuring points. The data acquisition software allows storing, visualizing and treatment of experimental data. A number of tracer experiments in one of Polish petrochemical factory in full scale conditions were carried out. The RTDs of both phases (wastewater and sediment) in processing units were obtained and correlated with sediment deposition map on tank bottom, and oxygen concentration distribution. The results of tracer experiments, carried out in different conditions (flow rate, sediment contents etc), gave possibilities to propose the model of liquid and sediment flow patterns and check the adequacy of tanks construction with theirs function.

6.1.2. Equalizer- clarifier tank.

Many sewage 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. The use of these tanks protects biological processes against sudden changes in impurities and pollutants concentration.

Quite often are used combined equalizer-clarifier units that simultaneously with equalization realize the sedimentation process as well. Homogenization in vessels can be accomplished by agitation, by recirculation or by the use of split flow systems. First two methods require the large power consumption for agitation or water pumping. Therefore, systems with split of input or output flow into a number of flows are also used.

The wastewater was charged 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=5000 m^3, the diameter D=40 m, and flow rate q=230 m^3/h. 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. Parallely the samples of inlet and outlet sewage, for measuring their technological parameters (COD- chemical oxygen demand, TSC-total sediment contents) were taken.

Fig. 43 shows the equalizer-clarifier unit of a wastewater treatment system where the radiotracer tests were conducted to investigate the homogenization and sediment removal efficiencies.

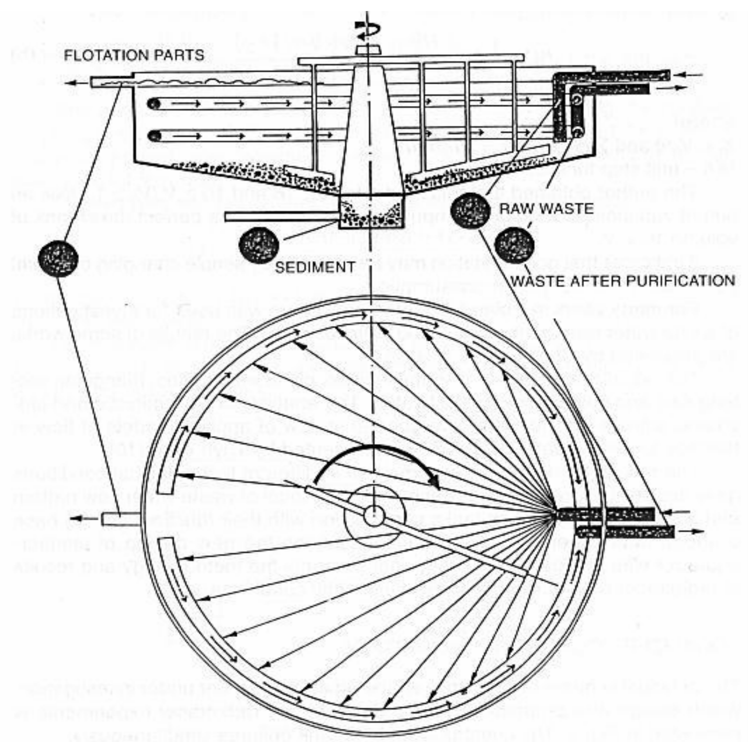


FIG.43. Scheme of equalizer-clarifier tank.

The experimental RTD curve is presented in Fig. 44. The MRT (mean residence time) was calculated as T=15.7 h. The value of dead volume d=25%.

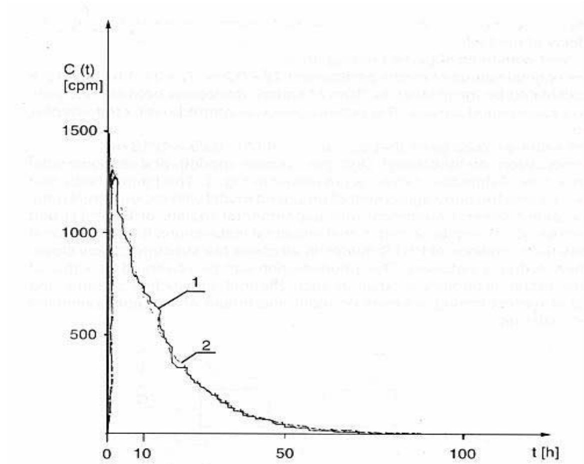


FIG.44. Comparison of experimental(1) and model(2) RTD functions.

The simple model of wastewater flow in tank consisting of delay, two perfect mixing units in series with time constants T_1 and T_2 and dead volume V_d was proposed (Fig.45). The optimal values of model parameters were found: T_0=0.2 h, T_1=15.4 h, T_2=0.2 h. Comparison of theoretical (for chosen model) and experimental RTD curves presented in Fig.44 showed good fitting of both curves.

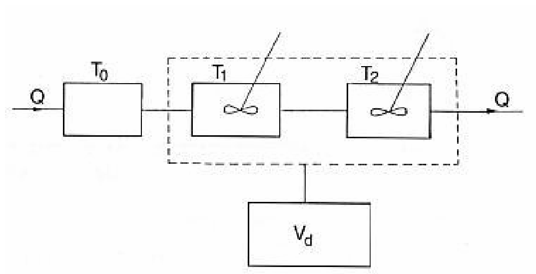


FIG.45. Proposed conceptual model of the sewage flow. Q-flow rate, V_d-dead volume, T_0- delay, T_1,T_2- time constants.

The values of measured COD (60%) and TSC (90%) indicated that significant reduction of them was achieved in this unit. The smoothing of fluctuations of output/input flow rates was also observed (SD_{out}/SD_{inp} = ¼).

6.1.3. 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.

Unfortunately, for the moment do not exist universal rules and correlations concerning the designing of these kinds of mixers for different geometries, flow rates, flow condition etc. 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
- petrorafinery 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 presented in Fig.46. The output of mixing wastewater is organized by overflow. The water form systems S1 and S4 are feeding on the free surface of liquid in mixer (in jet forms).

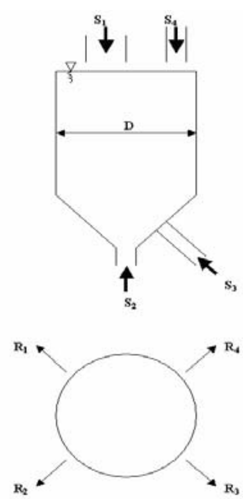


FIG.46. Scheme of jet-mixer (S_1÷S_4 sources of water, R_1÷R_4 streams feeding the biological reactors).

Radiotracer was injected continuously in each of streams S1, S2, S3, S4 with constant flow rate, until the tracer concentration in output stream of mixer remained more or less constant. A few samples of water directed to each reactor (R1-R4) were taken and theirs tracer concentration was measured. Mean tracer concentration $\overline{x}$, standard deviation σ and mixing index are presented in Table VIII.

For each tracer experiment the mean concentration and standard deviation were calculated; the ratio of standard deviation to mean value was considered as an index of mixing. From table VIII appears that the wastewater from S1 was homogenized only; other streams S2-S4 were not well mixed. It seems that wastewater from sources S2 and S3 (fed in bottom part of mixer) are preferentially directed to reactors R1 and R2. The computer fluid dynamics (CFD) simulation of liquid flow jets S2 and S3 in mixer was performed to find the flow structure inside the mixer. The CFD simulation is presented in Fig. 47.

TABLE VIII. MIXING CHARACTERISTICS

Labeled source	Tracer flow rate q [kg/min]	Reactors	Mean tracer concentration $\overline{x}$	Standard deviation σ	Mixing index: $M = \frac{\sigma}{\overline{x}} \cdot 100\%$
S_1	0.2	R_1	46,7	3,1	6,6
		R_2	42,9	2,3	5,4
		R_3	52,1	0,8	1,5
		R_4	51,7	1,5	2,9
S_2	0.022 ± 0.003	R_1	42,8	12,7	29,7
		R_2	41	12,7	31
		R_3	14,8	5,3	35,8
		R_4	13	5,1	39,2
S_3	0.015 ± 0.002	R_1	56,2	18,5	32,9
		R_2	66,4	17	25,6
		R_3	13,6	2,8	20,6
		R_4	13,8	4,2	30,4
S_4	0.018 ± 0.001	R_1	1,2	0,2	16,6
		R_2	1,1	0,2	18,2
		R_3	42,5	5,1	12
		R_4	42,5	6,1	14,3

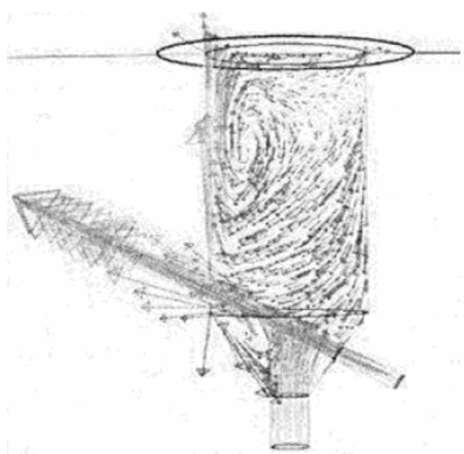


FIG.47. CFD simulation showing flow structure of jets S_2 and S_3 inside the cylindrical mixer

Using the CFD code the numerical RTD function was obtained (Fig.48).

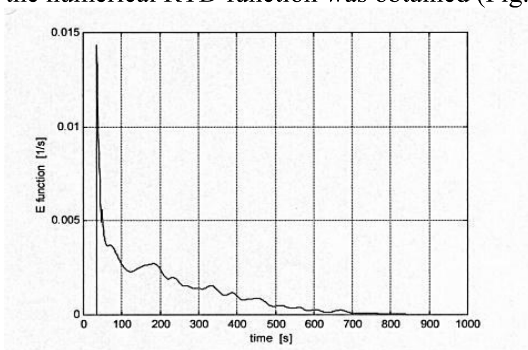


FIG.48. Numerical RTD function of two jets mixer (Volume V=28,5 m^3, flow rates Q_2=Q_3=200 m^3/h).

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 with five jets entering from bottom side. The CFD simulation was performed for the new design, and the RTD function was calculated from CFD code (Fig. 49). The most adequate model describing the flow structure in the proposed geometry of mixer appeared to be series of two unequal ideally mixer and plug flow.

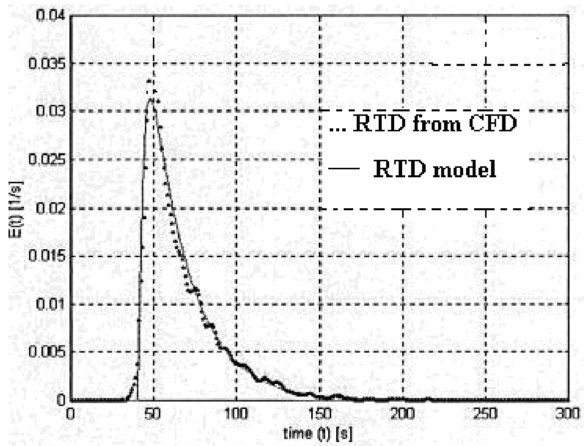


FIG.49. Comparison numerical and model RTD functions.

6.1.4. Aeration tanks

In biological aeration chambers organic compounds are removed from wastewater by microorganisms in the presence of sufficient quantity of oxygen, which is supplied by surface aerators or by systems of immersed perforated pipes located in bottom part of chamber. The great influence of water and sediment flow conditions on process efficiency was reported.

An industrial aerator was investigated using La-140 as a radiotracer of sludge (solid) flow parameters and fluoresceine as a water tracer. The aeration chamber design is presented in Fig. 50. Total volume of tank was V=1850 m^3, flow rate Q=180 m^3/h (with 50 m^3/h sludge recirculation), sediment contents 4-8 g/dm^3.

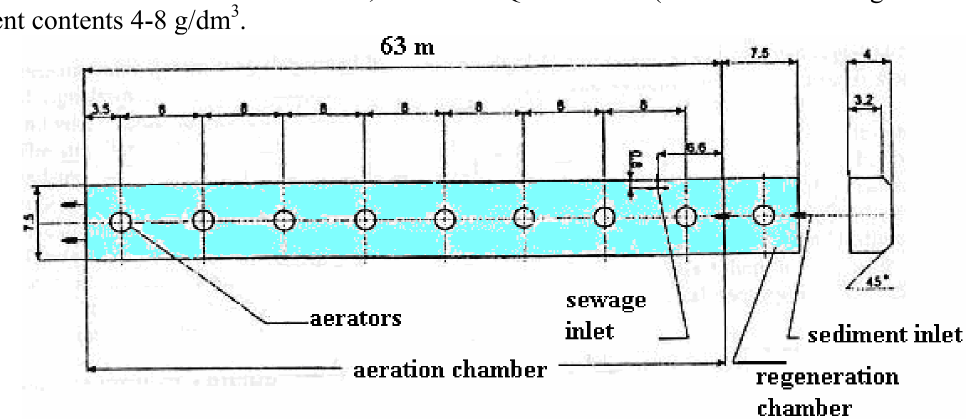


FIG.50. Scheme of biological aeration chamber.

The RTD functions for sediment and water in chamber were practically the same so it was not observed any significant separation of water and sediment flow. The rate of dead volume was about 10%.

6.1.5. Settlers

Separation of suspended sludge particles from wastewater, after aeration tank, is realized most frequently by gravitational force in the secondary settler (clarifier). Settler design can be circular or rectangular. During last years many radiotracer applications were carried out for investigating solid and liquid phase movements in both types of settlers.

a. Rectangular settler.

Series of laboratory and industrial scale tests of rectangular settler were carried out. The scheme of laboratory installation is presented in Fig. 51.

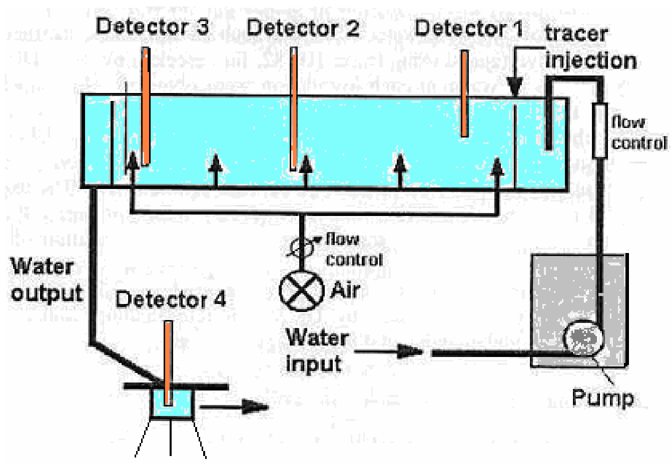


FIG.51. Scheme of laboratory rectangular settler.

Dimensions of tank were: L (length) x W (width) x H (height) = 4.9 x 1.3 x 0.45 m; volume V=2.93 m^3. Tracer tests were conducted for water flow rates Qw in the range 1-3.8 m^3/h, for different localization of baffles inside the settler, and for different systems of inflow or outflow.

Radiotracers Tc-99 and Br-82, as well as color tracer fluoresceine were used. The signals from detectors were recorded by multipoint measuring system. Experiments with Tc -99 from generator indicated sorption / desorption of Tc-99 on the walls of tank, so Tc -99 is not appropriate tracer for this kind of measurements. Reliable data were obtained using Br-82 radiotracer. Tracer tests in laboratory tests were compared with CFD simulation results. CFD numerical simulations were carried out using the CFD software Fluent 6.1. CFD code provided the velocity field in tank. The profiles of water axial velocity component in cross sections located 1, 2, 3 and 4, 5 m from tank input are presented in Fig.52.

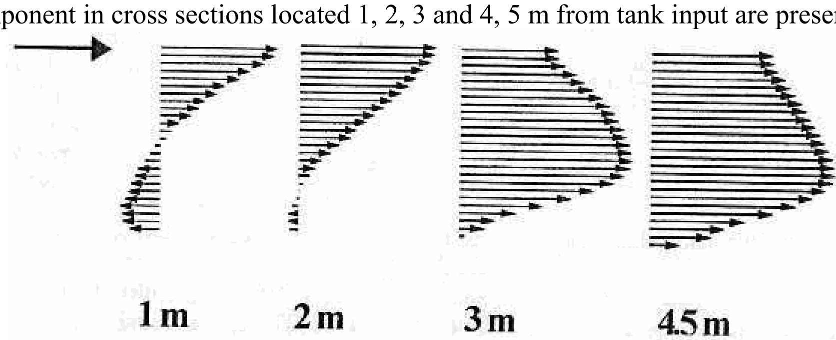


FIG.52. Profiles of axial velocity component in cross sections located 1, 2, 3, 4, 5 m from water input.

The presence of backflow, which included about the half of tank volume, was observed. The five parameters model was proposed for flow structure description - Fig.53.

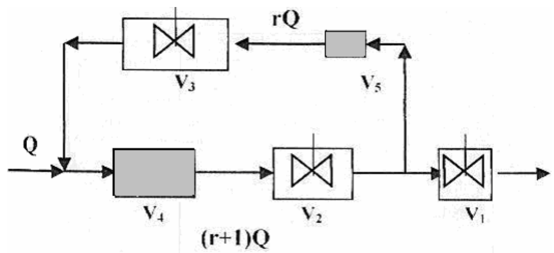


FIG.53. Model of water flow in settler

Using CFD calculated velocity field (Lagrangian method) the numerical RTD function was calculated. The comparison of both numerical and experimental RTD functions is presented in Fig.54. The accordance of both curves was acceptable.

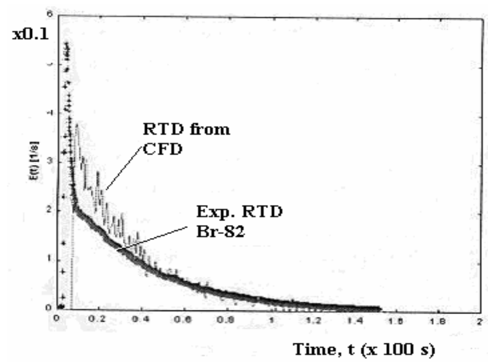


FIG.54. Comparison of experimental and numerical RTD functions for settler.

6.2. RADIOTRACERS FOR INVESTIGATION OF SOME WASTEWATER TREATMENT UNITS IN KOREA

6.2.1. Radiotracer experiment on a sand filter of WWTP

A sand filter operating in KAERI's 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.

Indium-113m (In-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 was used as water tracer to investigate the flow dynamics of wastewater through the sand filter system.

As shown in the figure 54, ^{113m}In-EDTA was injected just before the pump guiding wastewater into the sand filter. Two radiation detection sensors (D1 and D2) were placed between the pump and the sand filter to measure the tracer response curves.

The experimental RTD curve was measured at the exit of the sand filter (Detector D2 in fig. 55). It showed a typical curve of two tanks in series perfect mixers with a normal tail. The experimental mean residence time was found of 747 s.

Detectors D6 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 mean residence time was calculated 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.

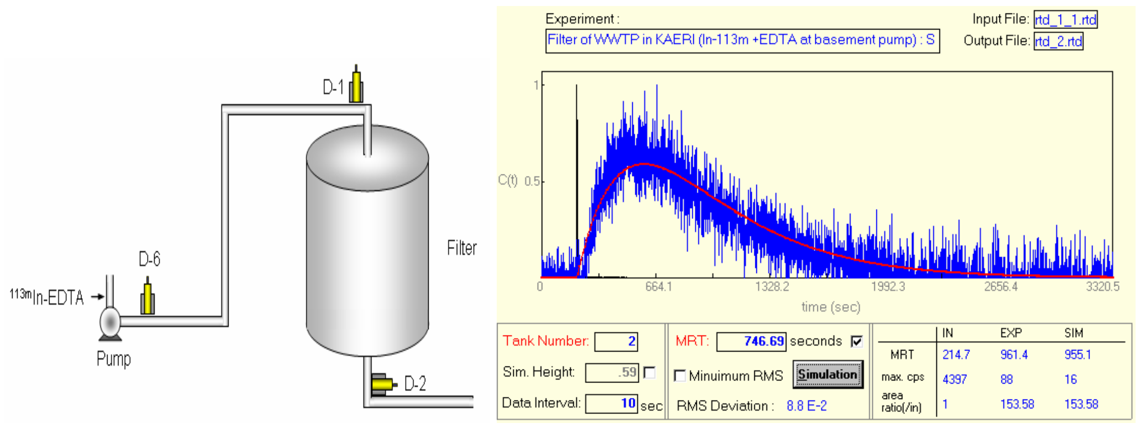


FIG.55. Diagram of radiotracer experiment on a sand filter and the RTD curve.

Particle carryover test was not performed for the filter, but In-11m can be a good radiotracer in order to evaluate solid removal efficiency of a sand filter.

6.2.2. 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. 56) which has only a gas bubbling mechanism in the primary digester and none in the secondary digester for the mixing.

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 two years ago 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.

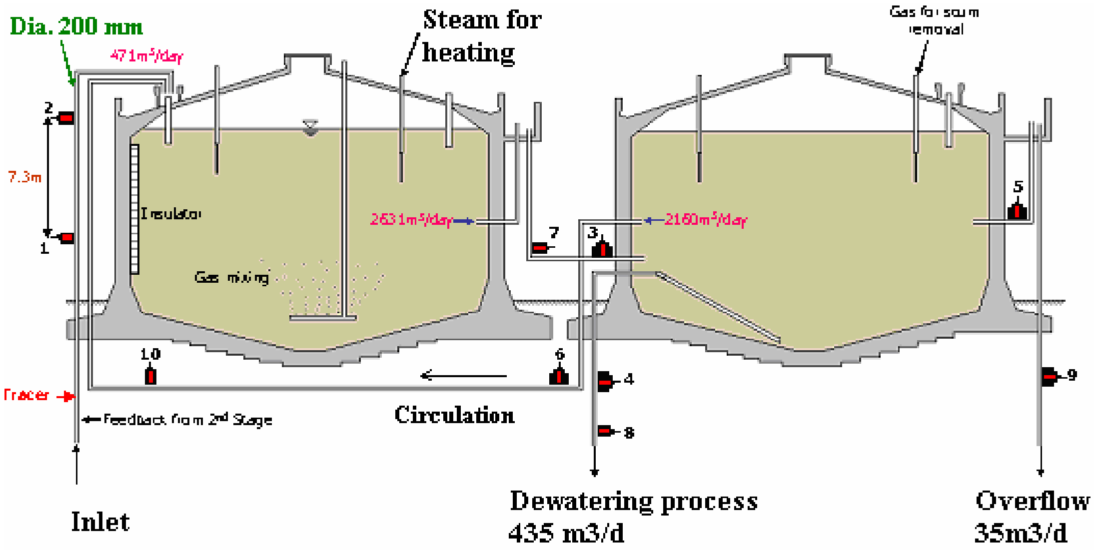


FIG.56. The diagram of the cylindrical 2-stage sludge digester.

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 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.

The experimental RTD profiles obtained from the outlets of the digesters are shown in Fig. 57. The curve from the overflow outlet of the secondary digester fluctuated due to the flow varies along with the operation condition but the pattern could still be used for analysis with no problem. At the position leading to the dewatering process the radiotracer concentration came back to the background level periodically because another digestion unit neighboring those under investigation discharges sludge to the dewatering process through the same passage and the sludge is flowing backward to those detectors.

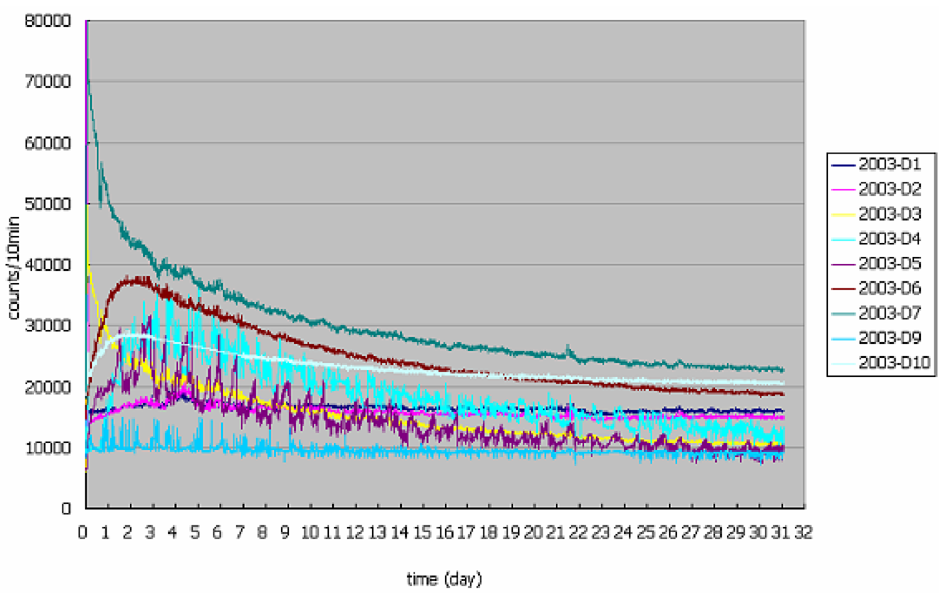


FIG.57. The response curves of the installed detectors to the radiotracer injection.

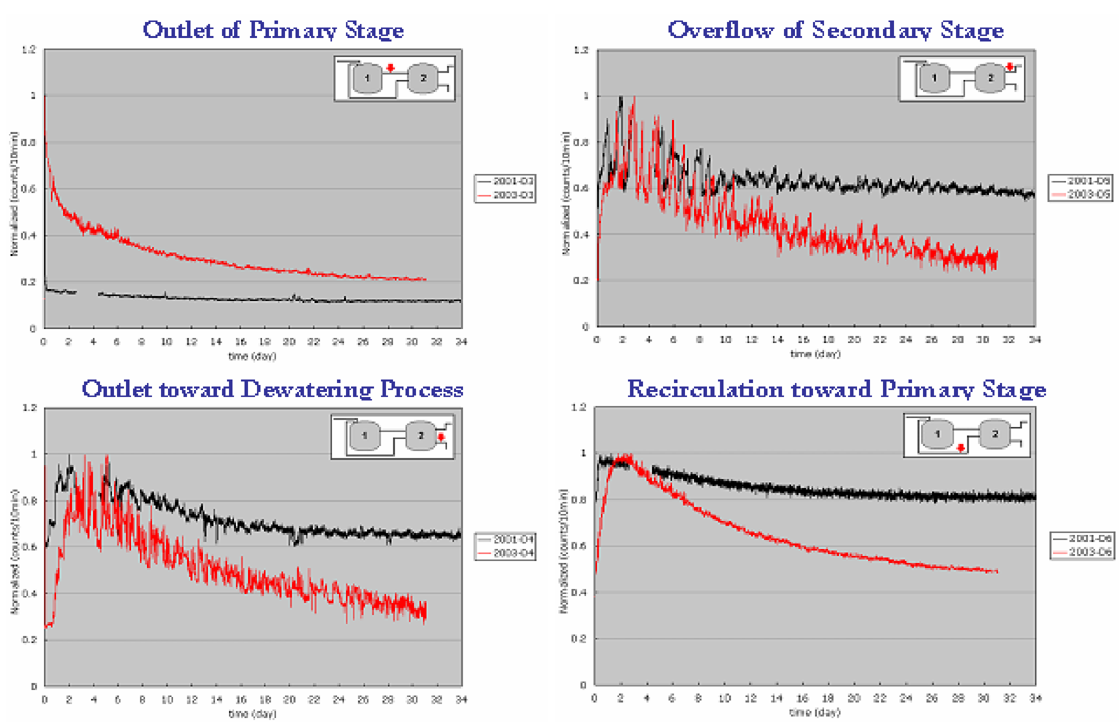


FIG.58. RTD Comparison between before and after the clean-up.

In order to compare the flow patterns before and after the cleaning work, the RTD curves from each experiment are plotted in Fig. 58. 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. This phenomenon matches the change of the break-through time and the maximum concentration time.

RTD analysis by perfect mixer models

In Fig. 59 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. 60.

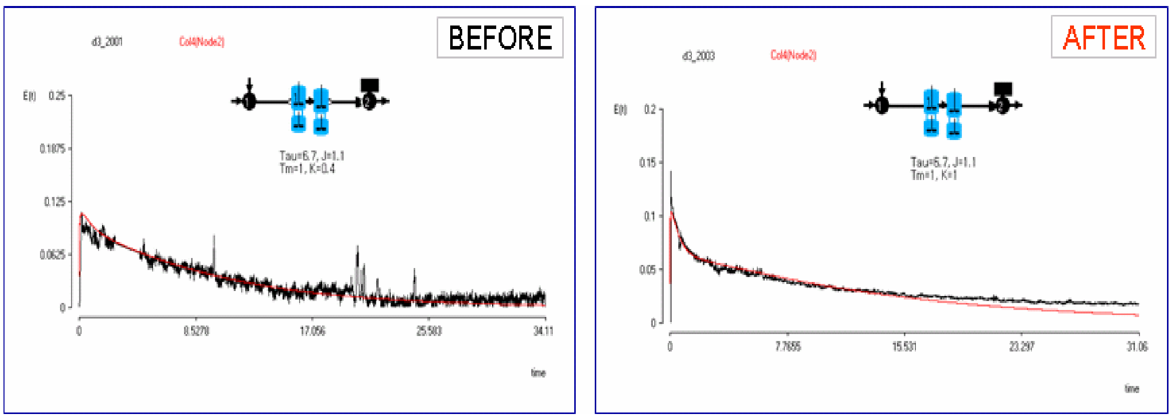


FIG.59. RTD Simulation for experimental RTD profiles obtained at outlet of the primary digester.

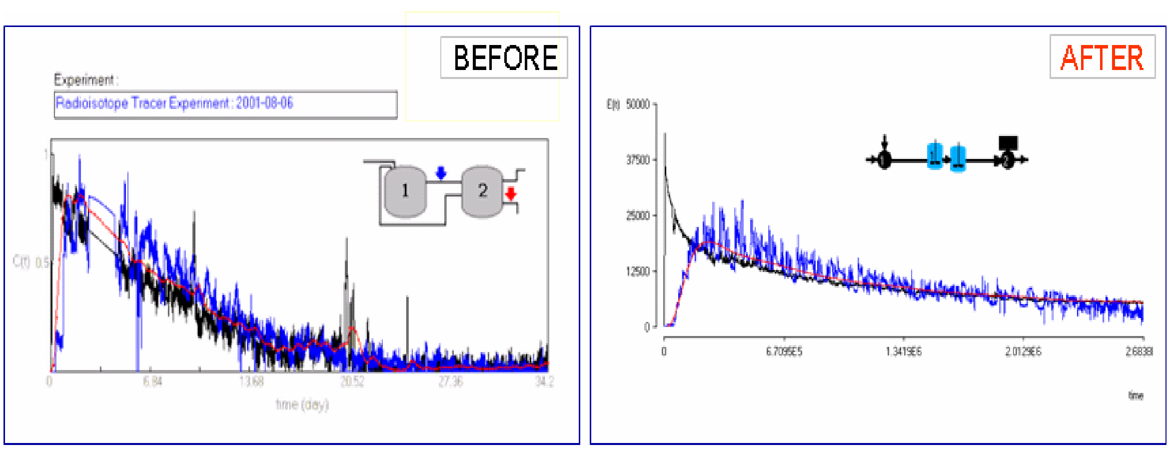


FIG.60. The results of RTD analysis on the secondary digester.

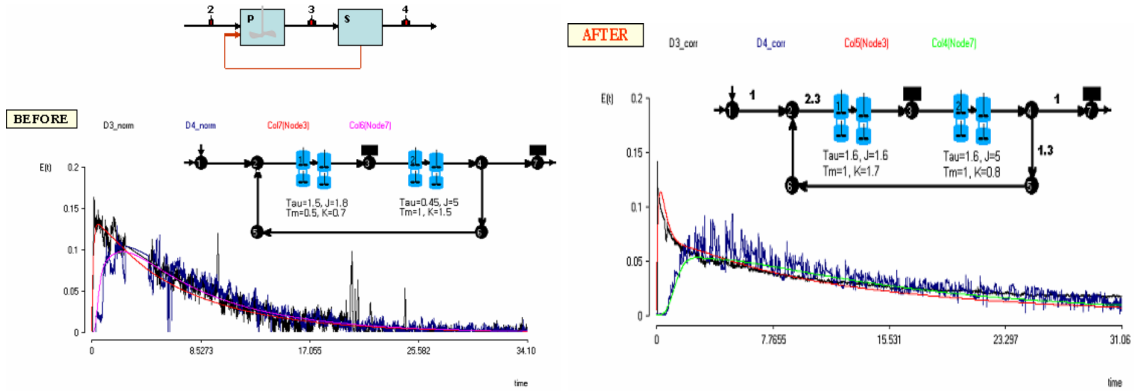


FIG.61. The simulation of the digester process using a numerical model.

The digestion process was simulated with the perfect mixers in a series with exchange volume. The results are plotted in Fig. 61. In contrast to the small increase of the MRT of the primary digester, the MRT of the secondary digester has been remarkably increased (Table IX).

TABLE IX. 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.

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

6.2.3. Validation of CFD model for a rectangular clarifier with radiotracer measurement

Settling by gravity is the most common and extensively applied treatment process for the removal of suspended solids (SS) from the wastewater. The performance improvement of a clarifier has been the subject of numerous theoretical and experimental studies because the investment for settling tanks in treatment plants is high as about 30% of the total investment and the effluent quality standard become more and more severe for the protection of environment.

The real time experimental RTD measurement is used to provide various important hydrodynamic parameters in a clarifier but it is not possible to visualize the detailed flow pattern inside a process system. On the contrary, CFD simulation gives visual understanding about a clarifier but needs to be validated for reliable prediction.

The objective of this study was to develop a computer program to predict the flow patterns and thereby to obtain an informative physical insight for a full-scale clarifier, together with the important parameters such as baffle configuration and empirical models of SS settling property.

The clarifier under investigation was modeled by 2-dimensional rectangular coordinate by the approximation of complex 3-D features of inlet and weir part in the clarifier (Figs. 62, 63). Special emphasis was given on the prediction of the removal efficiency of suspended solid (SS) together with the visualization of the calculated flow pattern in the clarifier. A control-volume based-finite difference method by Partankar was employed together with the SIMPLEC algorithm for the resolution of pressure-velocity coupling. The k-ε turbulence was incorporated for the evaluation of Reynolds stresses. Further a number of empirical formulas were considered for the modeling of SS and calculation of its induced density effect.

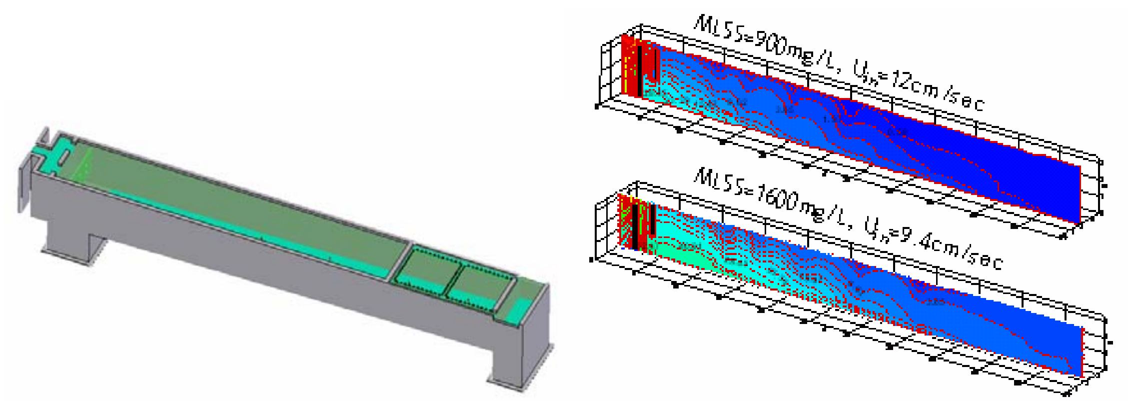
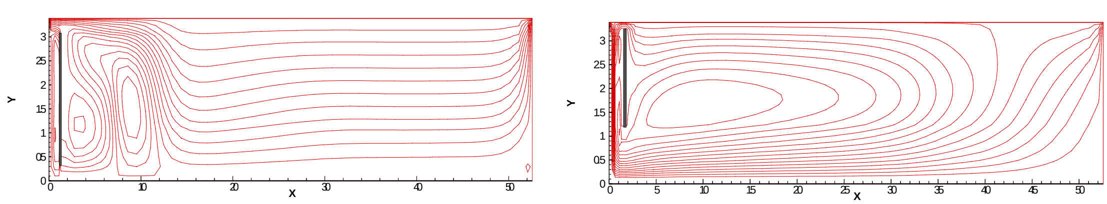


FIG.62. A rectangular clarifier and CFD simulation results.

Experimental data was obtained by the method of radiotracer (I-131, In-113m, Tc-99m), which is known as one of the robust visualization techniques in a full-scale flow field study. Comparison is successfully made on the calculated RTD curves with the radiotracer measurement inside the clarifier as well as the outlet. In detail, CFD model-based tracer concentration profiles are generally in a good agreement with the experimental RTD curves at the upstream and central section but a visible difference is observed at the location of discharging weirs (Fig. 64). This is partly caused by the fact that the radiotracer detection was carried out near the wall while CFD simulation profile was extracted from longitudinally centerline. Another reason is due to the limitation of present 2-D model to describe the complicate geometry of weirs.



(a) Neutral density condition (C_{in}=0 ppm) (b) Density effect (C_{in}=1300 ppm)

FIG.63. Contour of predicted streamline with density effect

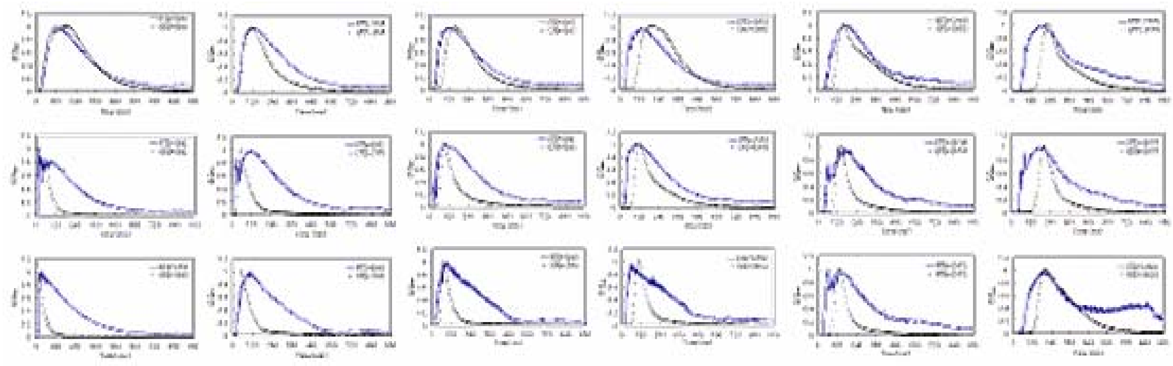


FIG.64. Comparison of radiotracer concentration profiles with CFD-based profiles

Further the calculation results predict successfully the well-known characteristics of clarifier flow such as the waterfall phenomenon at the front section of the clarifier, the bottom density current in the settling zone and the upward flow in the withdrawal zone, which are caused by the density effect by suspended solid (Fig. 65). Thus it is believed that the program developed in this study shows the possibility as a viable tool to assist in the design and determination of optimal operating condition of a final clarifier.

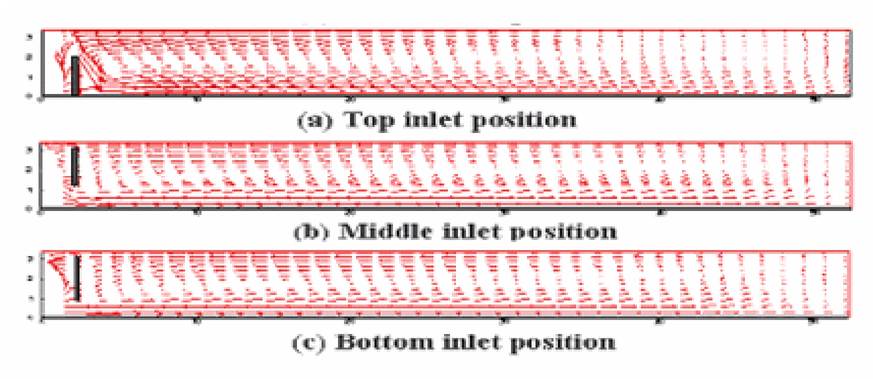


FIG.65. CFD simulation examples for investigation of inlet geometry

6.3. RADIOTRACER INVESTIGATIONS OF SEWAGE TREATMENT STATION, PAKISTAN

6.3.1. Objective

The scope of tracer 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. 66, including indication of localization of scintillation detectors during experiments.

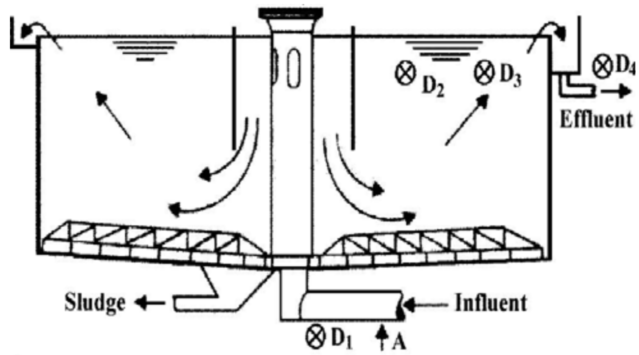


FIG.66. Design of center feed circular clarifier, A – tracer injection, D1-D4 – radiation detectors

The design (top view) of the aeration tank is given in figure 66. 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.

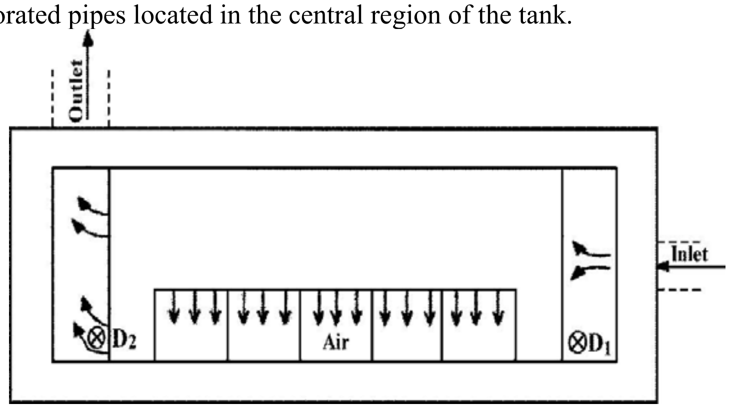


FIG.67. Design of aeration tank, D1-D2 – radiation detectors

6.3.2. 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 tracer was injected instantaneously (Fig. 68). Four signals (input, output and two signals from detectors immersed in water, located on bridge of scraper) for 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.

FIG.68. Radiotracer injection in the primary clarifier

6.3.3. Results

a. Primary clarifier

The experimental RTD curve obtained at the output of the primary clarifier (probe D4) is shown in Figure 69.

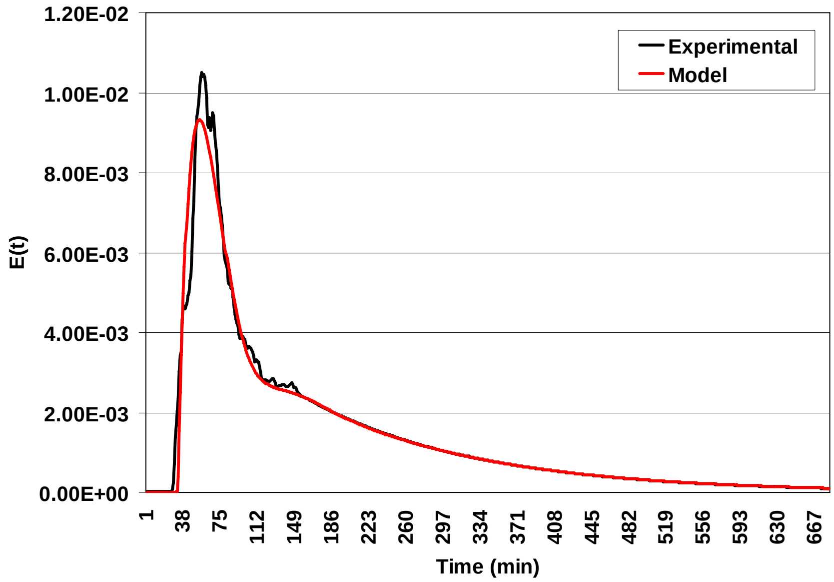


FIG.69. Experimental and model RTD curves of the primary clarifier.

The RTD software package (DTS PRO version 4.20) was used for treatment and modeling of the experimental data. Fig. 70 shows the selected model of primary clarifier, which fits better with the experimental RTD curve (Fig. 69).

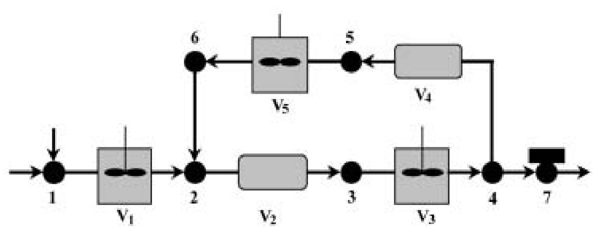


FIG.70. Model of a primary clarifier. V_1 = 96.2 m^3, V_2 = 285.78 m^3, V_3 = 201.8 m^3, V_4 = 76.3 m^3, V_5 = 199 m^3

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. 69) 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 165.7 min, i.e. very near to the experimental value of the mean residence time.

The volume of the primary clarifier was 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 the Figure 71. The best model found using RTD software is presented in the Figure 72.

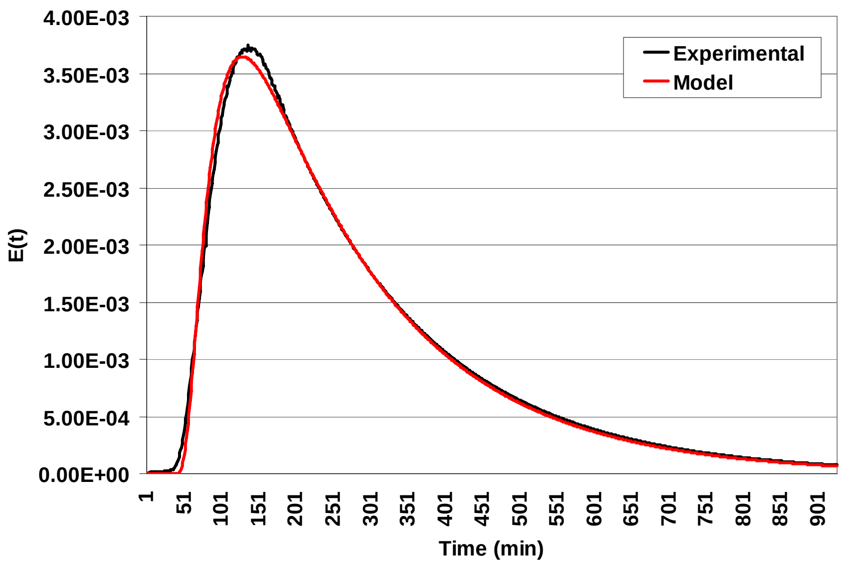


FIG.71. Experimental and model RTD curves of the aeration tank

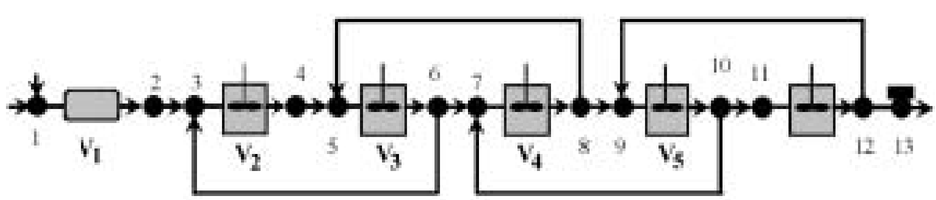


FIG.72. Model of the aeration tank. V1 = 80 m^3, V2 = 101 m^3, V3 = 100 m^3, V4 = 100 m^3, V5 = 97.7 m^3, V6 = 106.7 m^3.

The model consists of five perfect mixers in series with back mixing and connected with a plug flow reactor in 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%).

The mean residence time of the model curve was 268.7 min that is almost equivalent to the experimental mean residence time. The dead volume from the model is 1.5%. 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 Figure 73. Figure 74 shows the best model found using RTD software simulation.

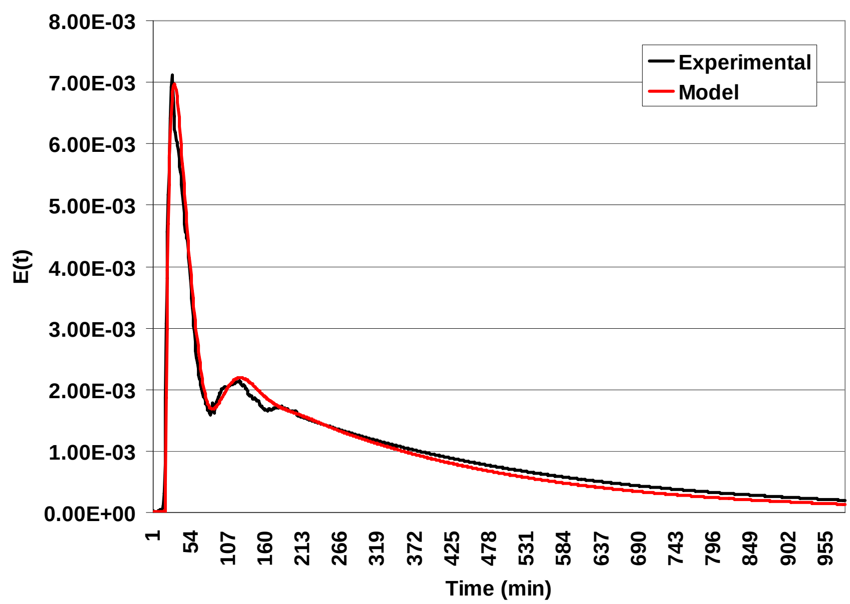


FIG.73. Experimental and model RTD curves of the secondary clarifier

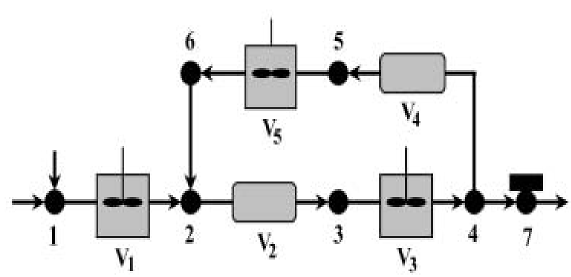


FIG.74. Model of the secondary clarifier

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. 73) 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.

6.4. RADIOTRACER APPLICATIONS FOR ENVIRONMENTAL INVESTIGATIONS IN FRANCE

6.4.1. Radiotracers for diagnosing the performance of a secondary clarifier

Radiotracer tests were used to diagnose the performance of a secondary clarifier (Fig. 75). Characteristics of the clarifier were:

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

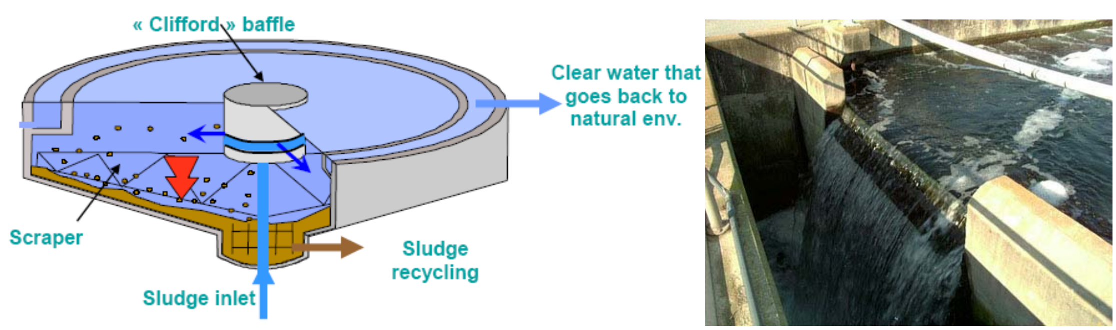


FIG.75. Scheme of the secondary clarifier

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. 76)
- 1 probe (D10) was placed inside the Clifford baffle at the entrance of the clarifier
- 1 probe (D11) was placed on the recirculation circuit between the center
- 1 probe (D12) was paced at the water outlet of the clarifier (discharge to the river).

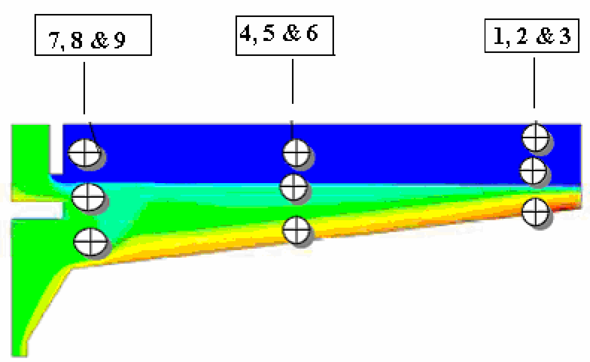


FIG.76. Positions of the 9 probes inside the secondary clarifier.

- 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 raw data for sludge experiment are presented in Figures 77-79.

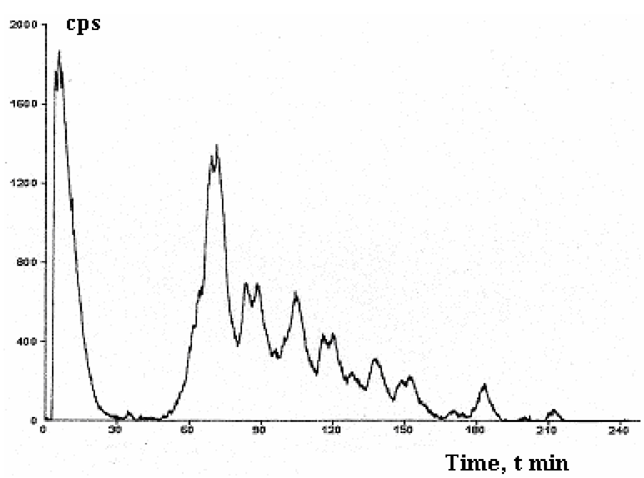


FIG.77. Experimental RTD curve obtained by probe D11 on the recirculation loop

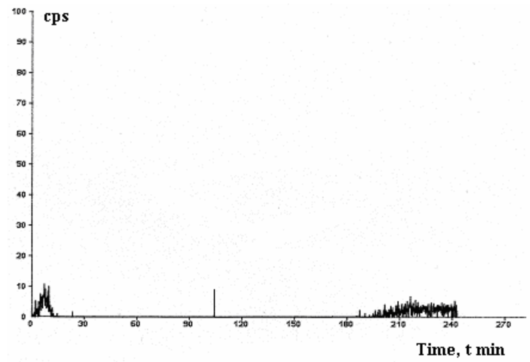


FIG.78. Experimental radiation measurement at outlet to river obtained byprobe D12

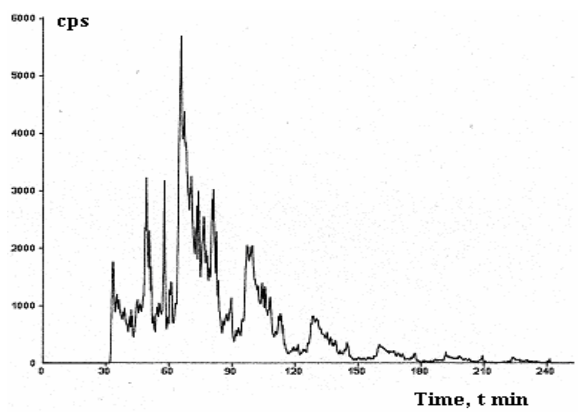


FIG.79. Experimental RTD curve obtained by probe D1 (distance to axis 9.85 m, height 30 cm)

Figs. 80-82 present some comparisons between CFD model and radiotracer experimental results.

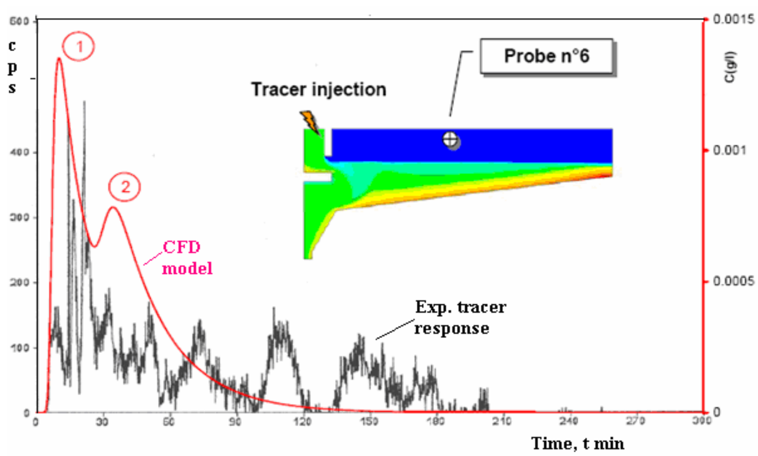


FIG.80. Comparison between CFD model and radiotracer experiment – Probe D6

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.

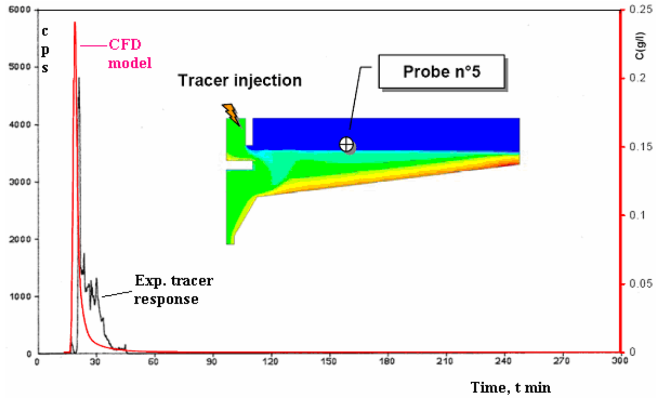


FIG.81. Comparison between CFD model and radiotracer experiment – Probe D5

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.

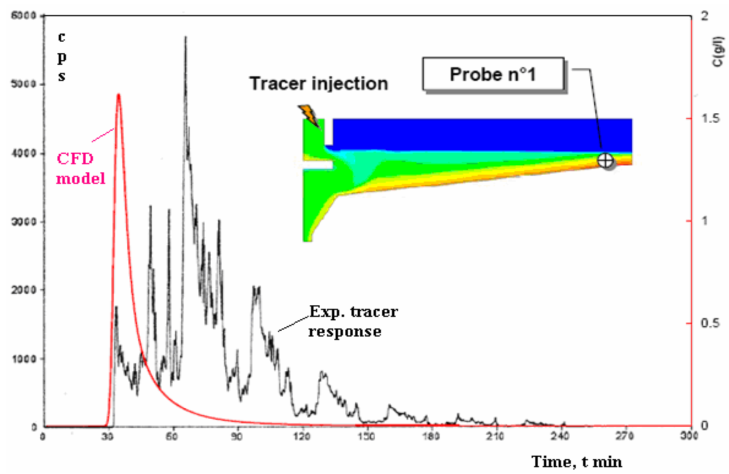


FIG.82. Comparison between CFD model and radiotracer experiment – Probe S1

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 computation.

Conclusion

For tracer experiments:

- Good repeatability of the results for the tests realized in the same functioning conditions
- 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 and internal age distribution of water and sludge inside the clarifier for various functioning conditions.

For the CFD model:

- Rheology modeling induces an important impact, realistic thickening and hindered effect on flow motion, highlights the scraper efficacy,
- Comparison with tracer studies gives relatively good agreement in region where the scraper effect is negligible (clarified zone & middle probes).

6.4.2. The investigation of anaerobic digester with radiotracers

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 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), because of the sensitivity of the measurements,
- because of 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 83 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.

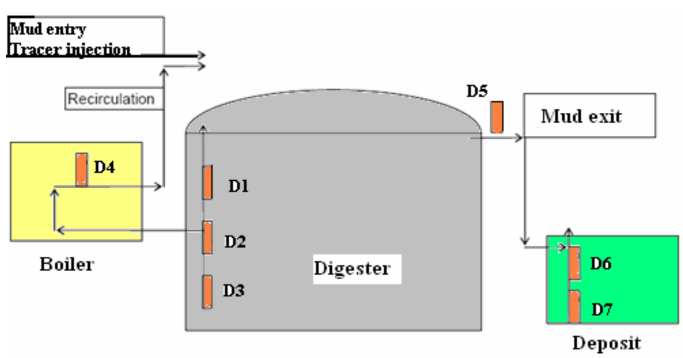


FIG.83. Schematic view of digester and location of detection points

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. 83) 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 optimum.

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,
- 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. Ir-191 was introduce in the glass preparation, which is easy activable in the nuclear reactor to produce Ir-192. 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” x 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 were 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) function only.

g. Mud dynamics

The signals recorded by the various detectors are illustrated in Figures 84 to 86. The signals relating to the detectors D_1 and D_2 have been normalized on the surface because they return well "to zero". This normation 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.

The examination of Figure 84 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 regarded as good mixed in the vicinity of the volume of detection of detector D_2.

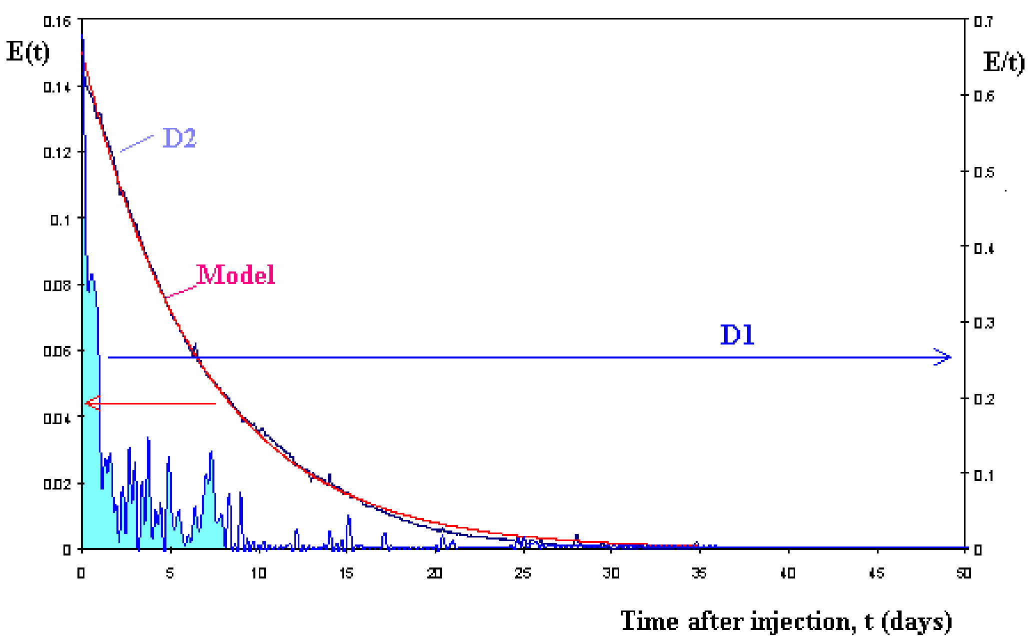


FIG.84. Experimental RTD curves for detectors D1 (at surface) and D2 (half depth).

The experimental RTD curve obtained near the bottom of the digester by the detector D_3 and its model are shown in Fig. 85. 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 figure is plotted for comparison the RTD obtained by detector D_2 (Fig. 84). 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.

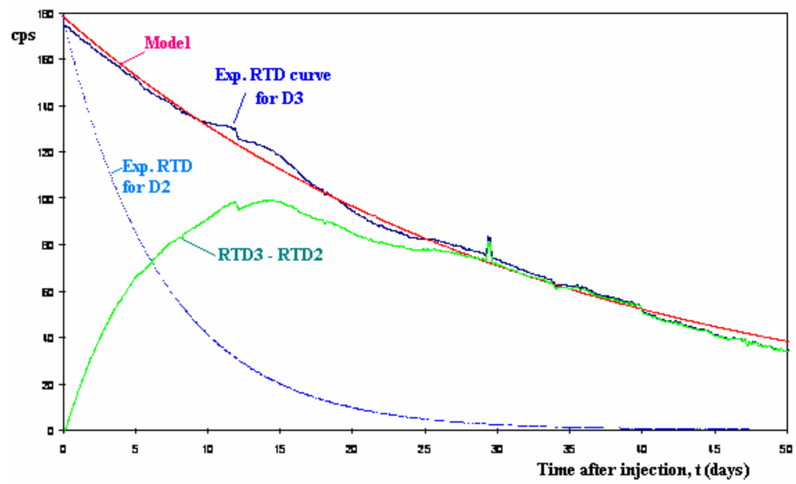


FIG.85. Experimental response for detector D_3 (digester bottom) an dits model

The experimental RTD curve obtained from detector D5 (mud exit) is given in Figure 86. It indicates that the digester behaviors like an "axial dispersion plug flow" than a perfect mixer.

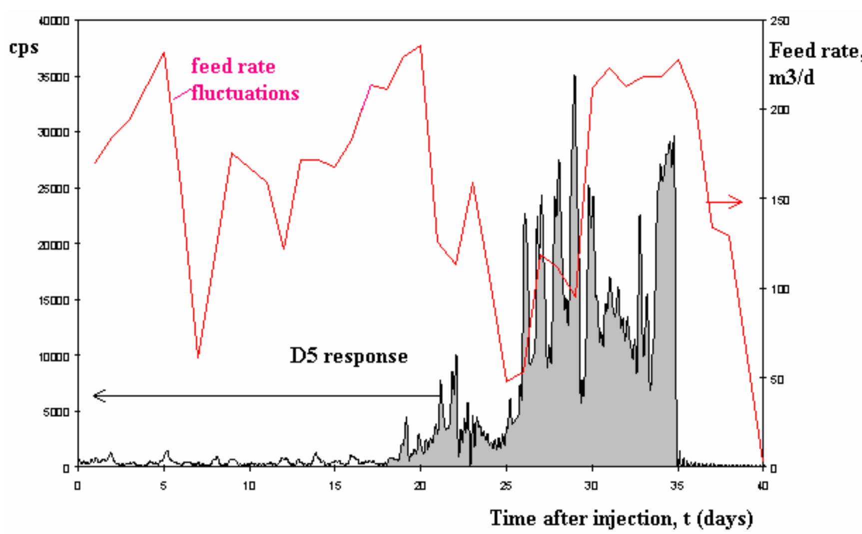


FIG.86. Experimental response of D5 (mud exit) and feed rate fluctuations.

To estimate the MRT of the mud inside the digester the correction of flow rate fluctuations has to be made. As seen from the Figure 86 the flow rate fluctuated during the tracer test duration (red line). It exists the relation:

$$Em = E(t)\ [Q(t)/Qm],$$

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 resulted that the average MRT of the mud inside the digester is 31 days that gives an active volume of 5000 m^3. The dead (stagnant) volume is calculated of 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 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. 87).

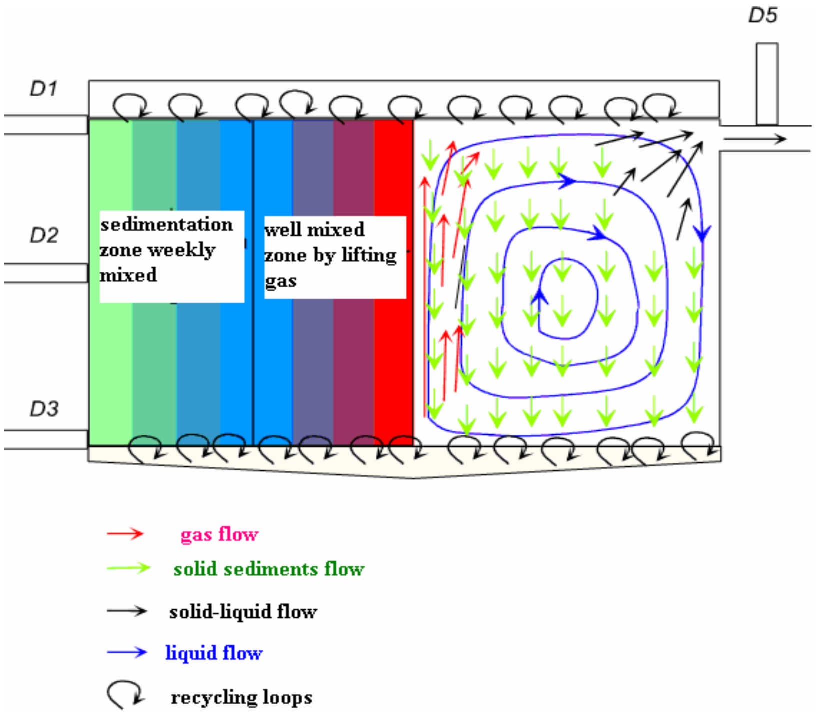


FIG.87. Possible model of mud movement inside the digester.

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 frein is responsible for the tracer dispersion at the exit of digester.

e. Sand dynamics

Fig. 88 shows the experimental RTD curves obtained for sand tracer by detectors D1, D2 and D3.

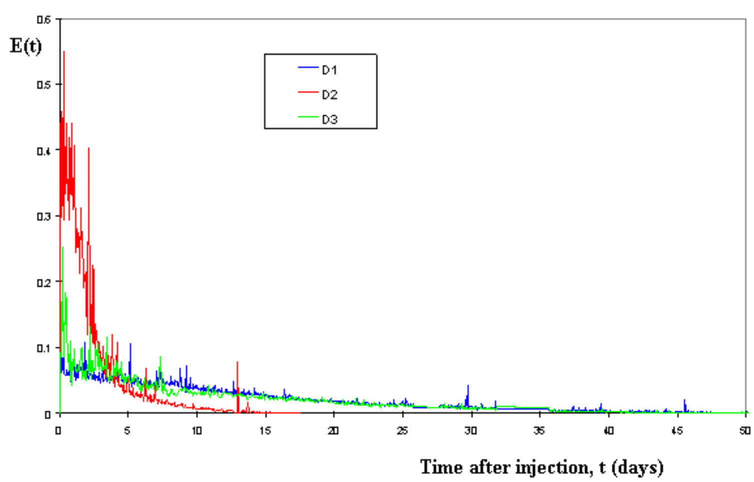


FIG.88. Experimental responses of detectors D1, D2 and D3 for sand tracer

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.

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 the Figure 89 and is correctly validated as prove it the Figures 90, 91 and 92.

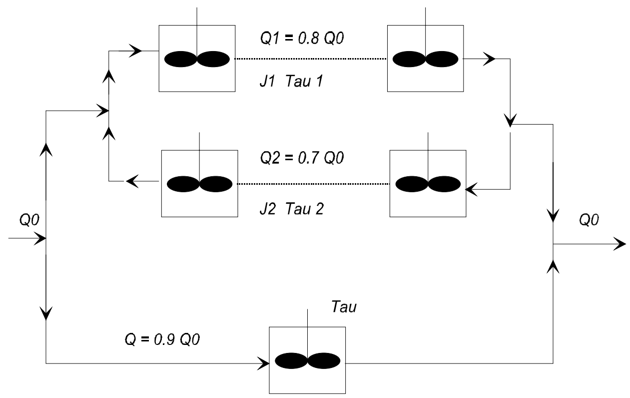


FIG.89. Modèle systémique de l'écoulement du traceur dans le digesteur.

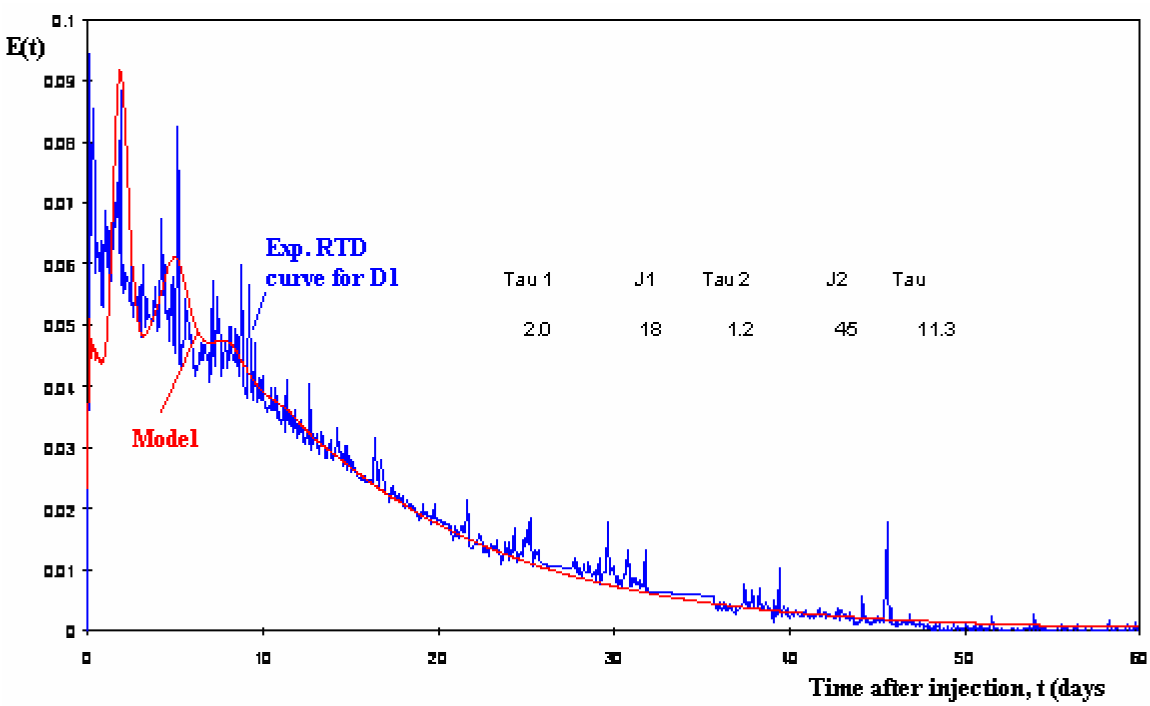


FIG.90. Experimental RTD curve and its model for D1.

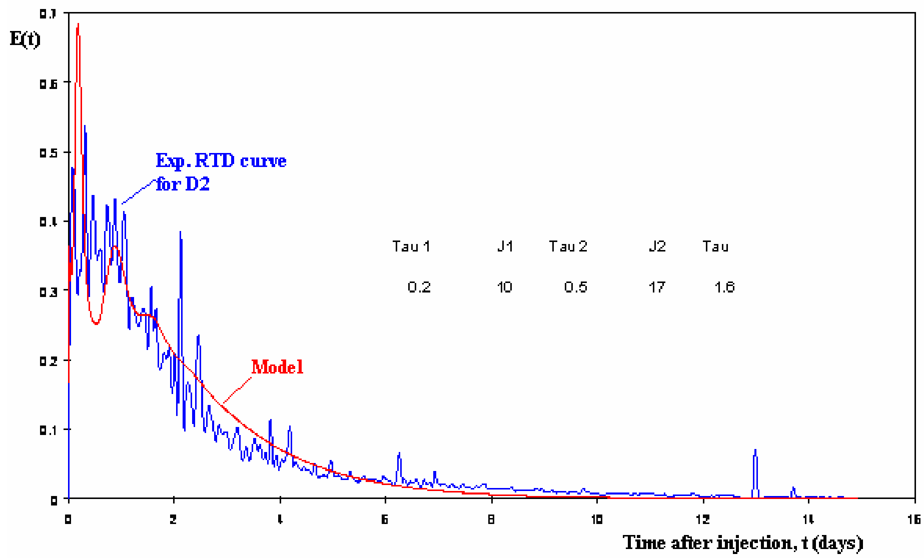


FIG.91. Experimental RTD curve and its model for D2.

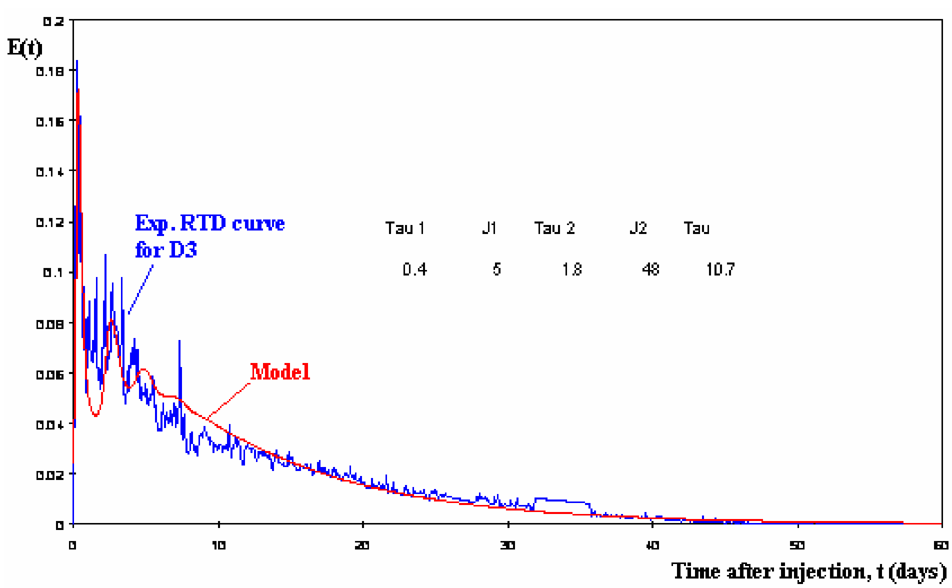


FIG.92. Experimental RTD curve and its model for D3.

In order to compare with the flows suggested on the left part of Figure 87, 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.

Actually, the behavior of traced sand must be comparable with that of tracer mud even if the corresponding signals obtained at the time of this preceding tracing do not have the same oscillations. In other words, the internal evolutions of these particles result only from the competition between sedimentation and the tendency to the homogenization (strong on surface and the bottom, weak with semi-depth) in the digester (Figure 87).

The difference between the time-constants of the evolutions of mud and sand in the digester comes then mainly from the differences between the trails of the traced particles (mud doped with hafnium or activated sand).

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.

Lastly, as in at the time of the tracing of mud, the RTD signal relating to the D_5 detector (placed at exit of the digester) (Fig. 93), shows that the digester cannot be overall related 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 medium flow of 135 m^3/d, 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 to the presence of zones difficult to reach to the sand flow.

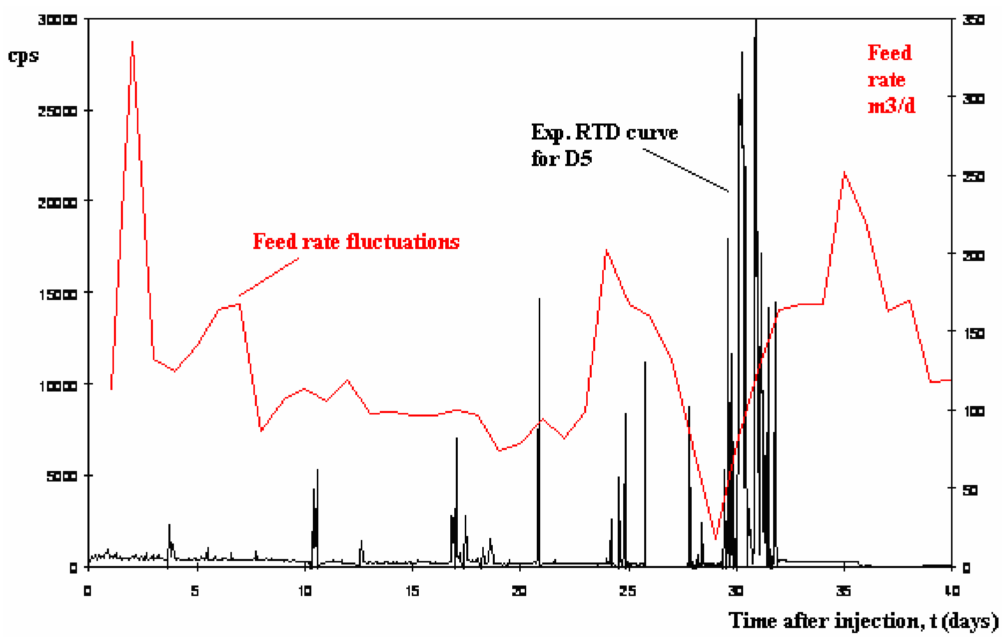


FIG.93. Experimental RTD curve for D5 (sand exit)and fluctuation of feed rates.

f. Conclusions

The radiotracer investigation made it possible to understand and quantify the complex internal mechanisms; a possible model of the digester was proposed. Mud and sand tracing provided their hydrodynamic behaviors and proposed a coherent structure of the principal flows inside the anaerobic sludge digester. 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 make possible to further 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.

6.5. MUNICIPAL WWTP: BIOLOGICAL AERATION TANK IN A WWTP IN DENMARK

6.5.1. Problem

The design of the biological aeration tank investigated using radiotracer technique is presented in Fig. 94. 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.

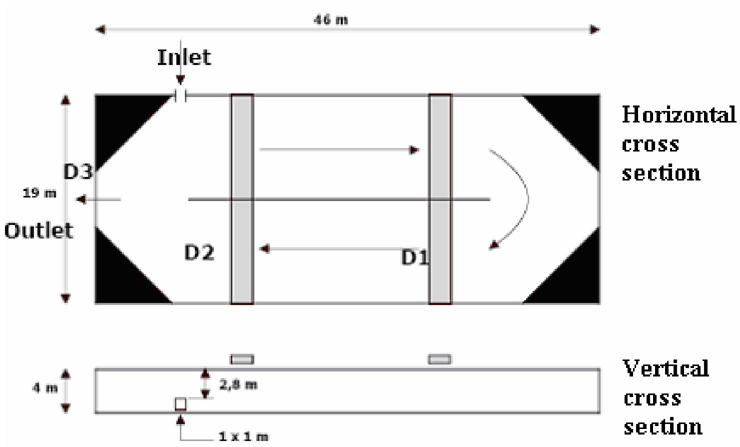


FIG.94. Biological aeration tank

6.5.2. Radiotracer test.

The radiotracer used for water phase was Br-82 as $NH_4{}^{82}Br$ (1000 MBq/injection). 500 mL tracer solution was pumped as an instantaneous injection down to label wastewater in the submerged inlet to the tank. Fig. 95 shows the injection system and the radiotracer mobile lab (inside the truck).

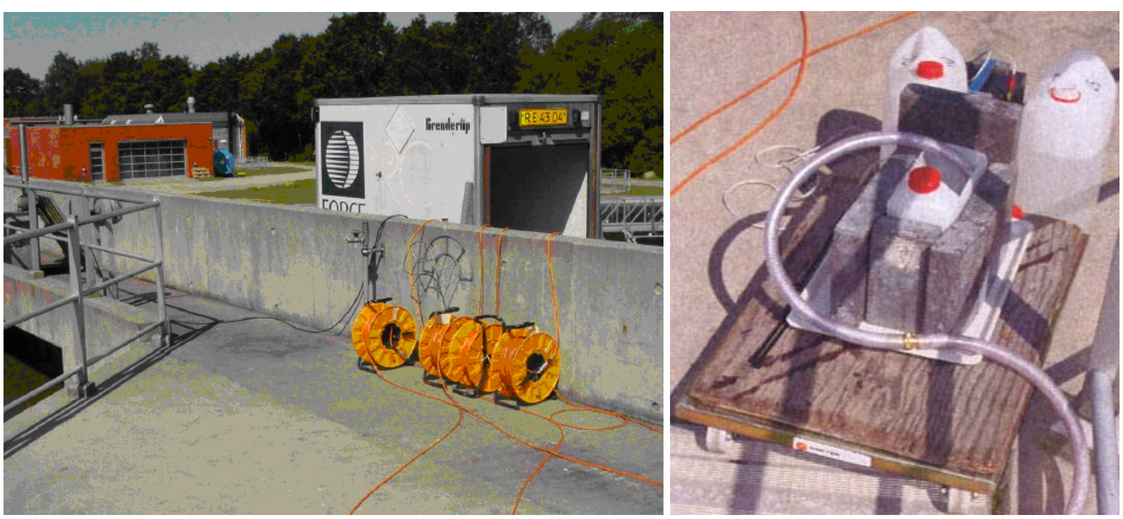


FIG.95. Mobil tracer lab and tracer bottle for injection

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. 94).

A third probe (D_3) was placed in a flow through detection chamber from the tank outlet (Fig. 96). Probe D_3 monitored the discharged effluent.

FIG.96. Location of probes: D_2 immerged and D_3 inside detection chamber

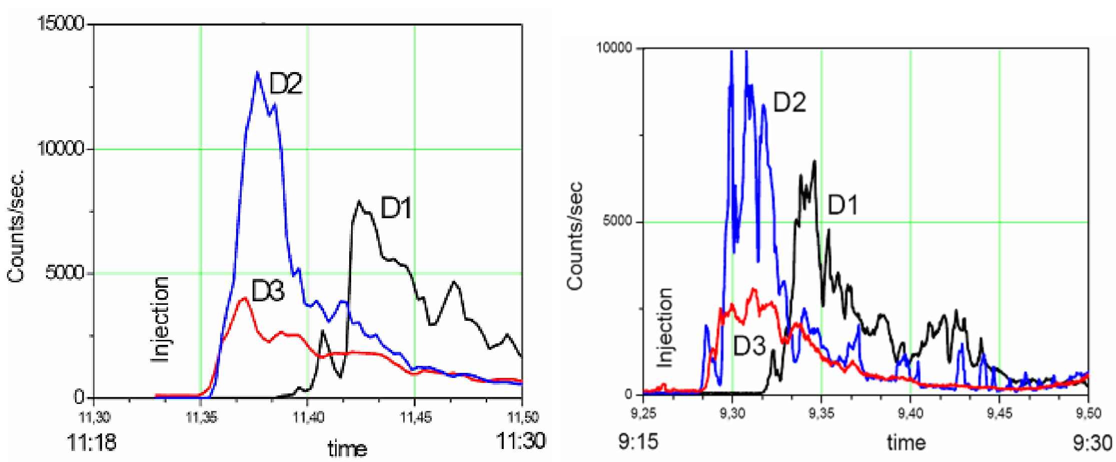


FIG.97. Experimental RTD curves in two tests

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. Figure 97 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.

6.6. ^{99m}Tc AS A TRACER FOR THE LIQUID RTD MESUREMENT IN ANAEROBIC DIGESTER: APPLICATION IN A SUGAR WWTP

6.6.1. 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 Au-198 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 (ICINAZ) 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.

6.6.2. 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 «Pablo Noriega» 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 with a rate of 0.4 Nm^3/kg of biodegradable COD, and the attain of sludge that constitutes and 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.

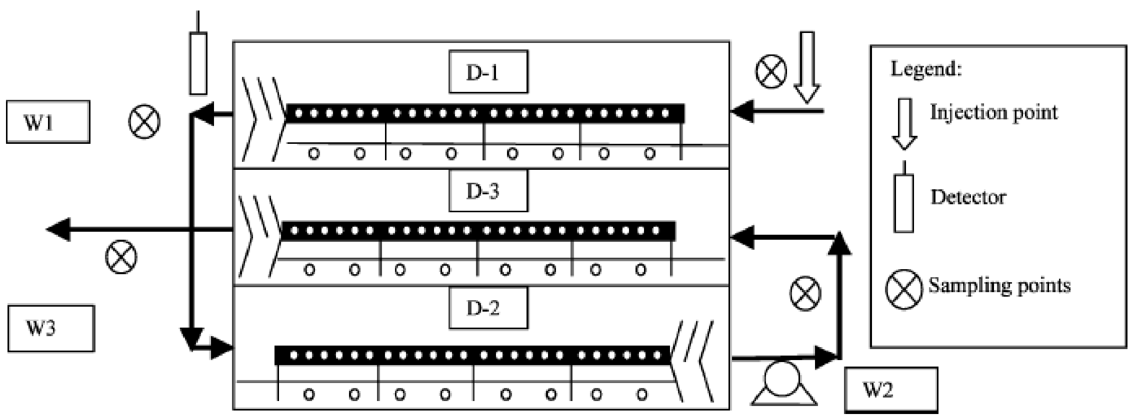


FIG.98. Scheme of the industrial unit

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’s going by gravity from D_1 to D_3 and from D_2 to the outlet (Fig.98).

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 (Intertechnique CG400, France). Furthermore, pH and Eh of the solution were measured. The percents of Tc sorbed *U(%)* were calculated through the expression:

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

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 = 14,4 m^3/s). A pulse of about 37 GBq of sodium ^{99m}Tc-pertechnectate, first elution of a ^{99}Mo/^{99m}Tc generator (Cis Bio International, France), 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, Australia). 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.

6.6.3. Results and discusions

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. Fig. 99 shows the experimental RTD curve and its model. For the simulation of such complex systems the software DTS PRO V.4.2 was employed. It allows the construction of any complex network of elementary reactors (such as plug flow reactor, perfect mixing cells in series and perfect mixing cells in series exchanging with a dead zone) properly interconnected and the optimization of the parameters of the experimental curve (Fig. 100).

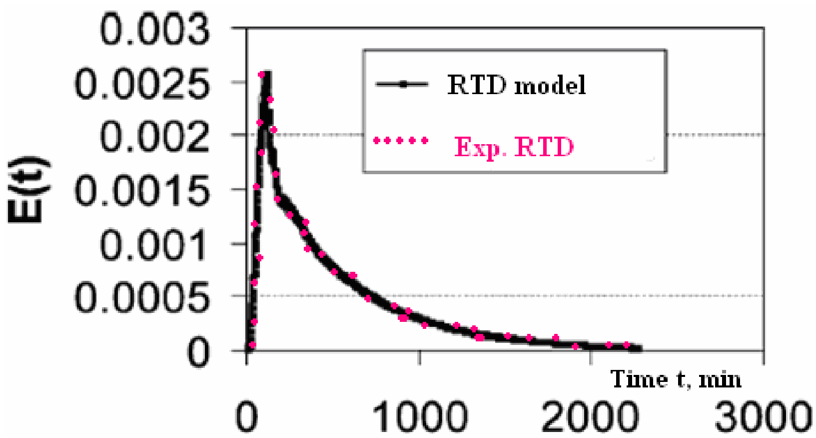


FIG.99. The experimental RTD curve and its model

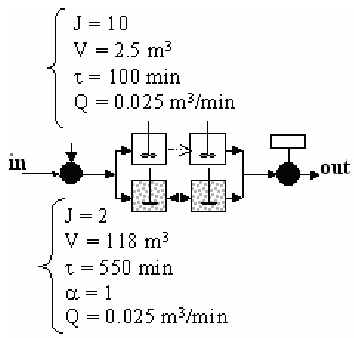


FIG.100. Model of the flow behavior in the first digester

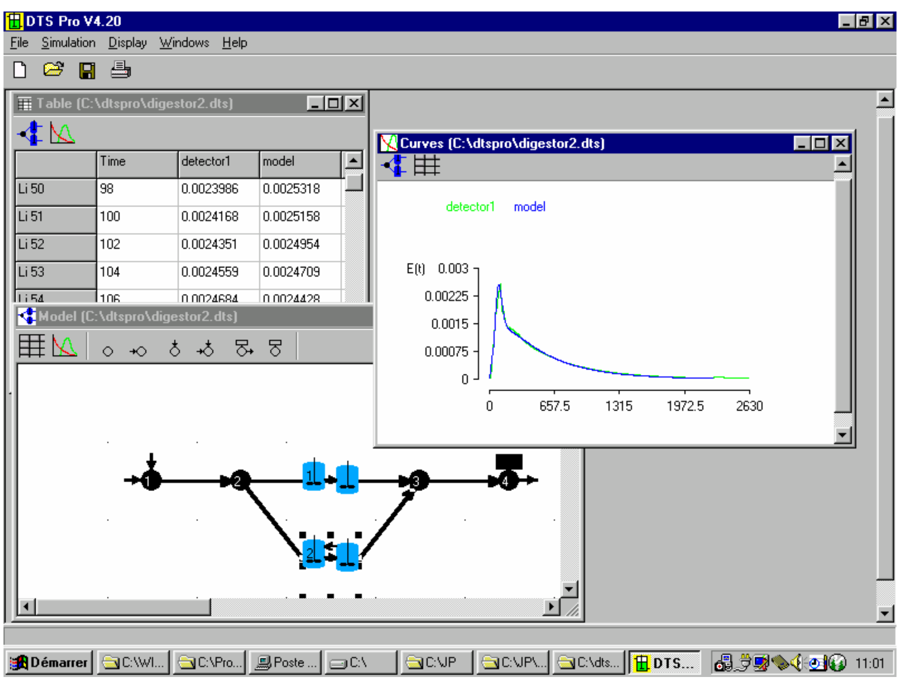


FIG.101. Modeling experimental RTD data with DTS software.

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. 101) 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.

6.6.4. Conclusions

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 from 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; Tc can be used as a tracer 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. The tracer may be used for any HRT measurement and modeling of the flow behavior in opaque industrial digesters.

6.7. EVALUATION OF SEWAGE TREATMENT PILOT PLANT USING RADIOTRACERS

6.7.1. Evaluation of mixing process in 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. 102).

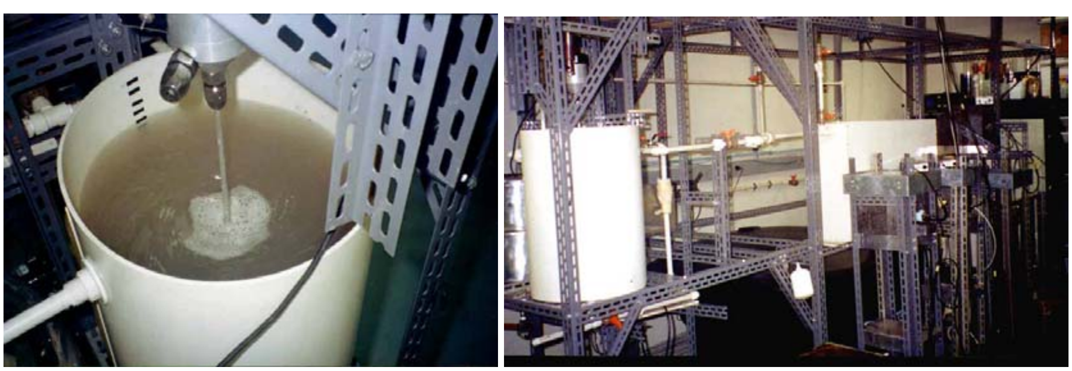


FIG.102. Equalization tank in laboratory scale

The unit consisted in an 80 liters PVC cylindrical vase with mechanical agitation (plain plates). 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”x2") 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 was injected directly in the sewer as a pulse, and its signal measure by the detector. Figure 103 shows the experimental RTD function, E (t), for the equilizer. The curve seems like a perfect mixer but, the measured MRT (22.6 min) 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.

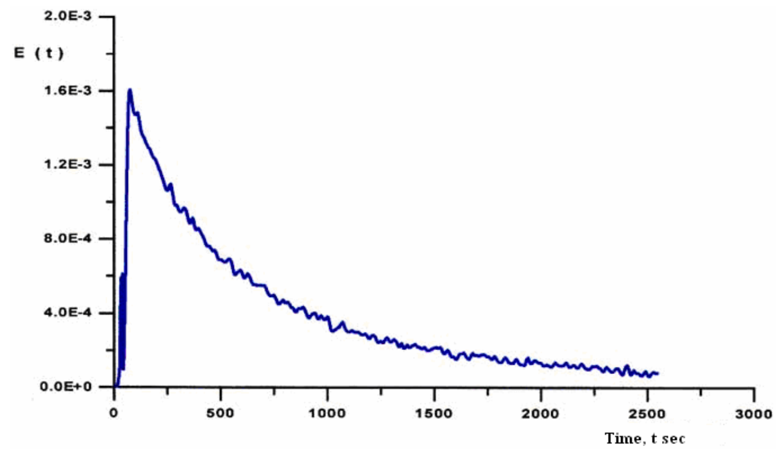


FIG.103. Experimental RTD curve of liquid phase in the equilizer

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. In the 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 Figure 104; they differ a lot because the hydrodynamics of both fractions are significately different.

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.

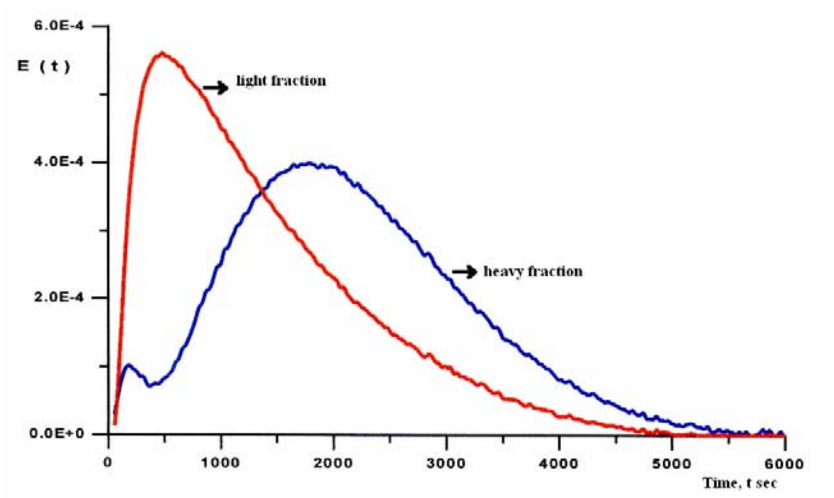


FIG.104. Experimental RTD curves for "heavy fraction"(^{140}La) and for "light fraction"(^{110m}Ag)

6.7.2. Measuring characteristics of settling tank

To analyze the process characteristics in settling tank of sewage treatment station a Cox laboratory model was built up (Fig.105).

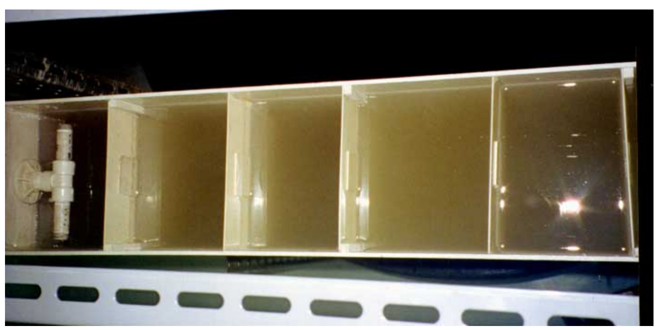


FIG.105. Laboratory settling tank

The tank was built in PVC, (rectangular form, 100,0 x 60,0 x 20,0 cm) with six internal walls (baffle plates of 45,0 x 20,0 cm) resulting in independent compartments where sedimentation process of the solid phase occurs.

Three detectors NaI (2x2") 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 (20cm) 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.

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 Figure 106.

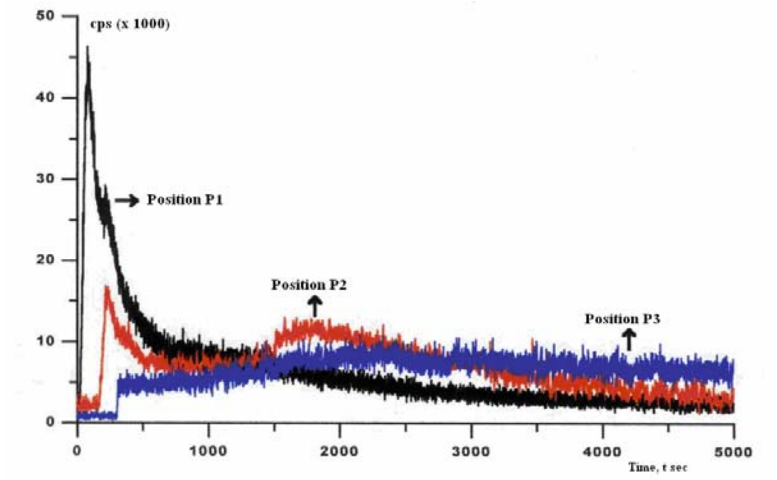


FIG.106. Characteristic curves of setlting tank for original design(single plate)

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 P1and P2 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

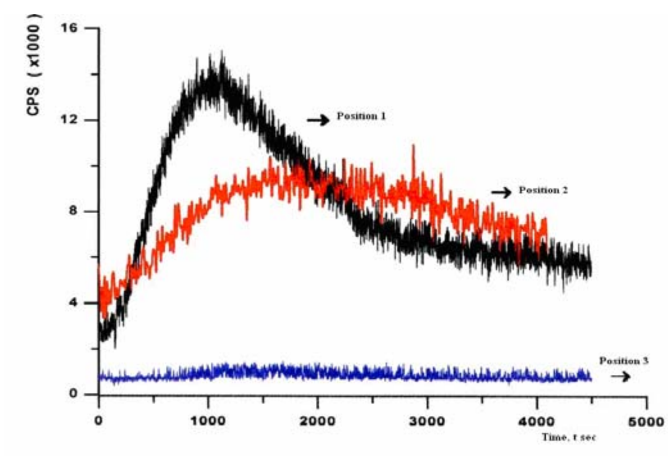


FIG.107. Characteristic curves of setting tank for optimized design(double plate)

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.

6.8. HYDRODYNAMICS STUDY IN AN AERATION UNIT OF A WWTP IN SWEDEN

6.8.1. 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. Computational 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.

6.8.2. 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. LiCl chemical tracer was injected as Dirac puls at the inlet of the aeration tank (Fig.108). The detection of tracer at the outlet of the system provides the residence time distribution (RTD) curve.

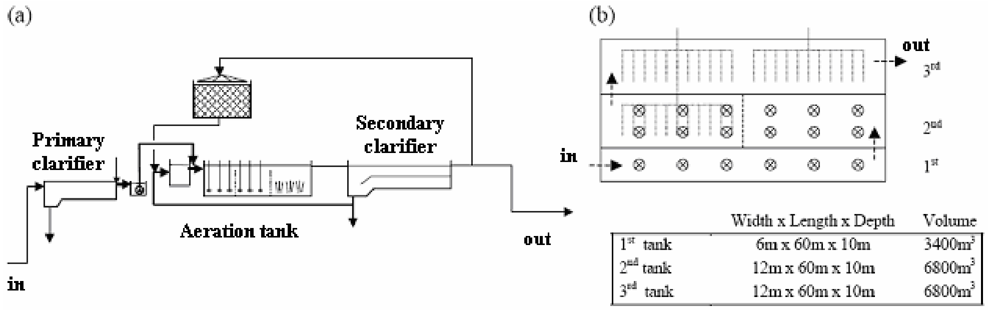


FIG.108. Tracer test in aeration unit, a. aeration unit design, b. Aeration unit compartments. Arrows indicate the flow direction.

The aeration system consists of three tanks in series (Fig. 108). Investigation of the hydraulic situation was performed in the first tank. Photos of the first tank are shown in Figure 109.

FIG.109. Photos of the first tank showing the tank without water. The supporting beams and mixers can be seen. (Photo: Gryaab)

The inlet has an area of 3 m x 2 m and is located in the upper part of the short side of the tank. The outlet (3 m x 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.

6.8.3. 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 presented as RTD-curves in Figure 110.

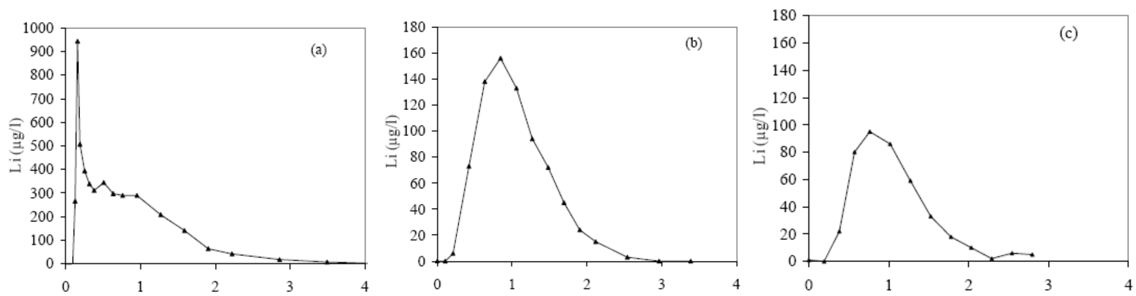


FIG.110. Experimental RTD curves showing lithium concentration detected in the effluent of (a) the first, (b) the second and (c) the third tanks in the tracer test.

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. 110a). The lithium concentration in the effluent of the second and third tanks reached maximum concentration at θ~ 0.85 (Fig. 110b), and θ~ 0.8 (Fig. 110c), respectively.

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 Figure 111. 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.

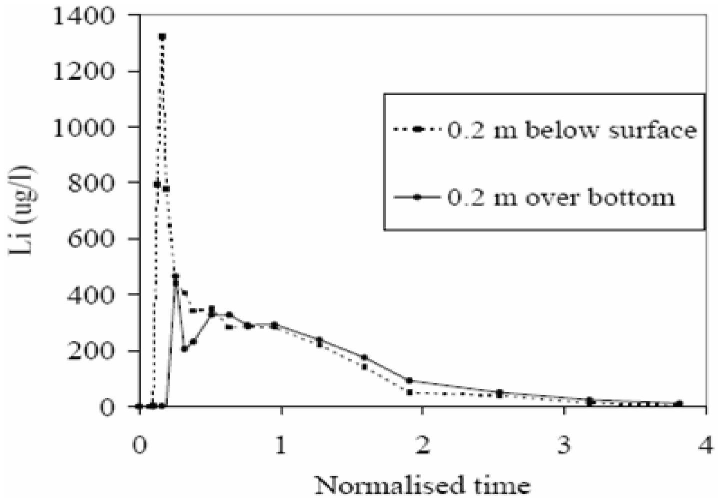


FIG.111. Experimental RTD curves showing radial gradients in effluent of first tank

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.112).

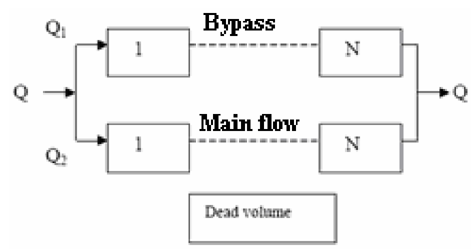


FIG.112. First tank model, tanks in series in parallel with dead volume

The results of modeling are plotted in Figure 113.

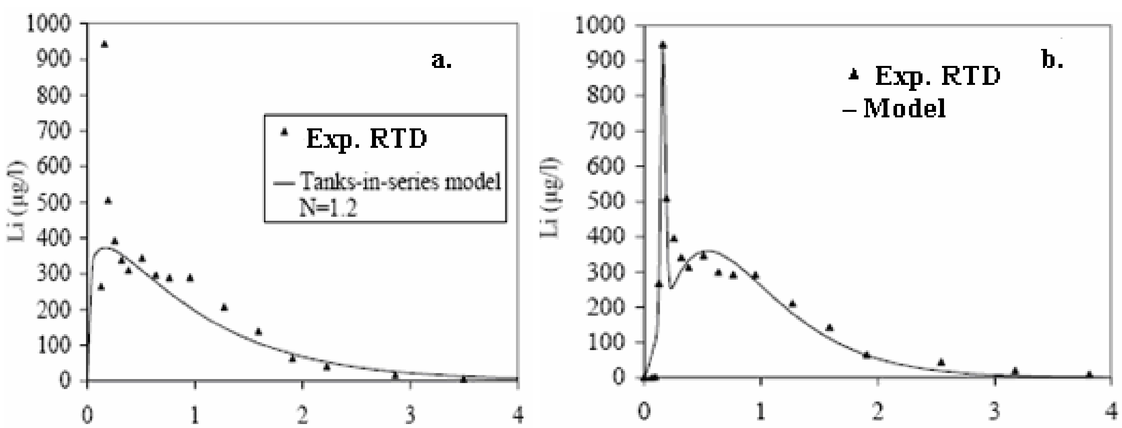


FIG.113. Modeling experimental RTD curve with a. tanks in series, and b. tanks in series in parallel with dead volume models.

As seen from Figure 113, 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. 114). As shown in Figure 102, 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).

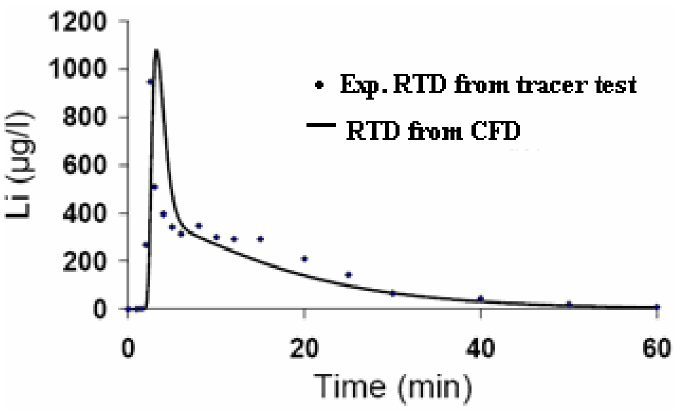


FIG.114. Experimental RTD curve and RTD curve generated from CFD simulation in the first tank

In addition, the CFD modeling provides the velocity map inside the aeration tank (Fig. 115).

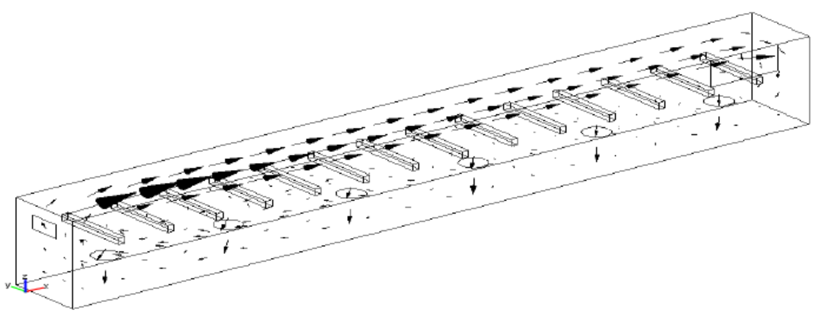


FIG.115. Velocity map obtained by CFD simulation

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).

Three main corrective measures were:

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

RTD curves generated from CFD simulations of different corrective measures are plotted in Figure 116.

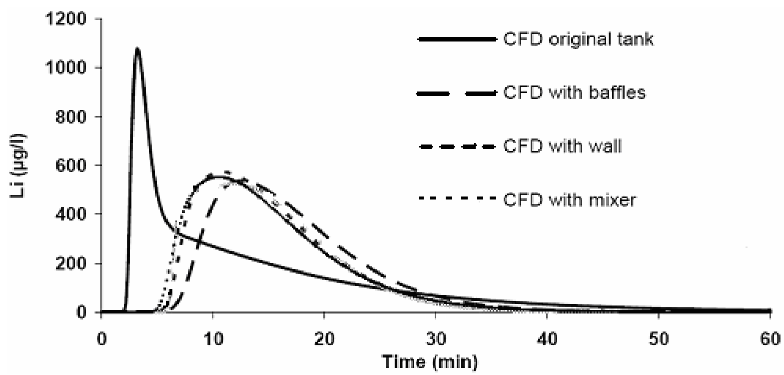


FIG.116. RTD curves generated from CFD simulation for different corrective measures

Figure 117 shows velocity maps obtained by CFD simulations for three different corrective measures.

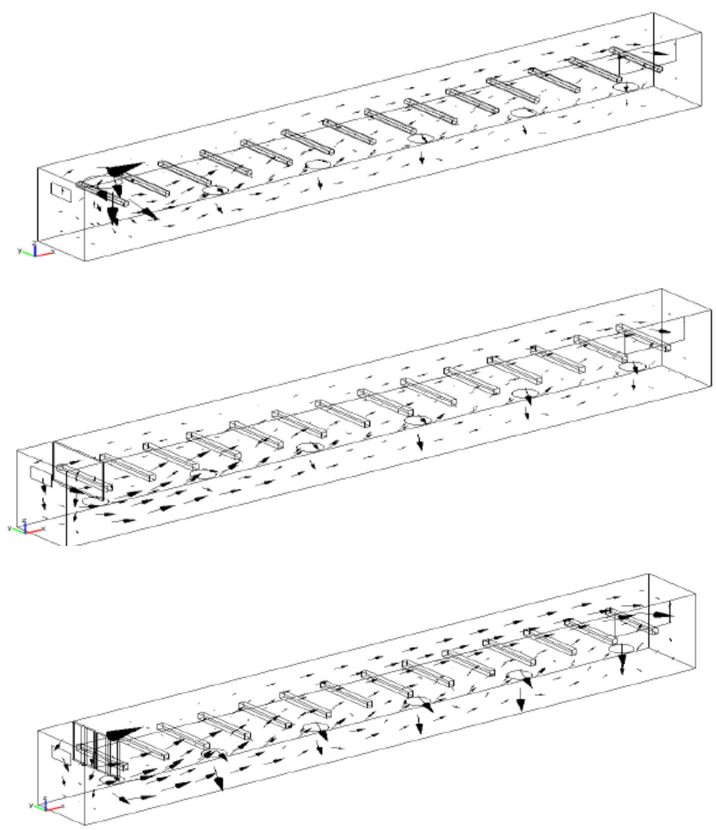


FIG.117. Velocity maps obtained by CFD simulation for three corrective measures

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 Figure 105 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 Figure 118 (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.

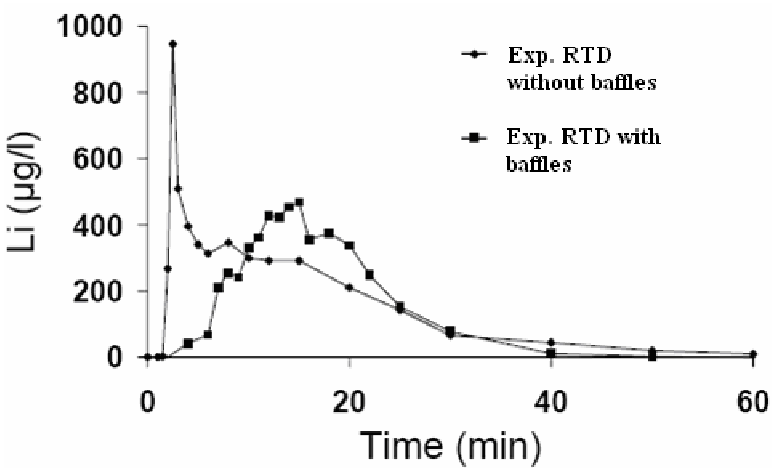


FIG.118. Experimental RTD curves without and with baffles

6.8.4. 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.

6.9. HIGH LOAD FIELD TEST OF A SECONDARY CLARIFIER IN A WWTP IN THE USA

6.9.1. 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. 119) 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.

FIG.119. Tracer test in secondary clarifier

6.9.2. 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. 119). 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 presented in Fig. 120. The current progressed uniformly toward the center.

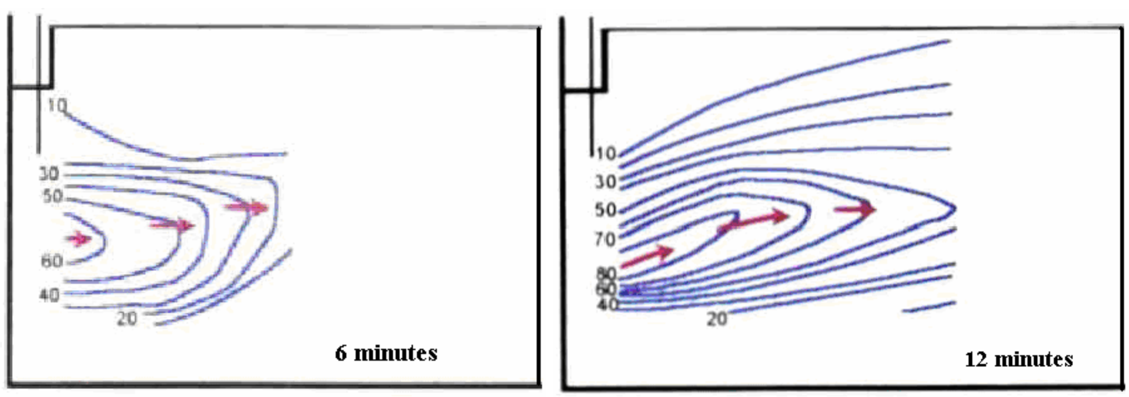


FIG.120. Tracer progression after injection

6.9.3. 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 presented in Fig. 121.

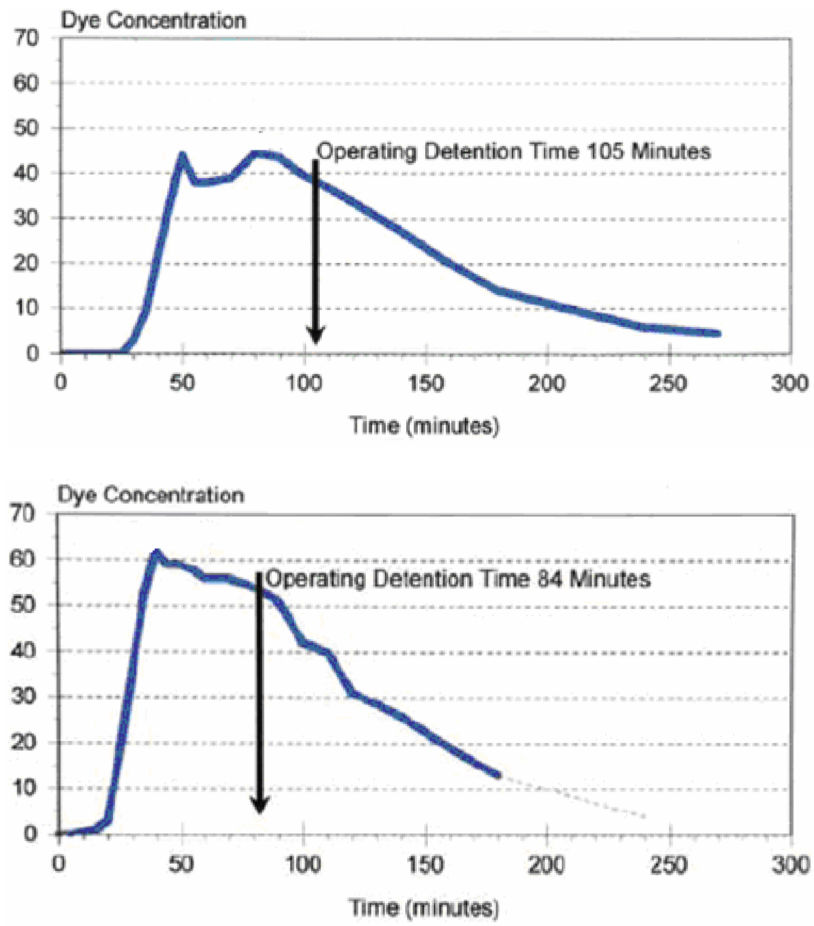


FIG.121. Experimental RTD curves in secondary clarifiers

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.

7. 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:

1. Collection of the basic data, references and technological knowledge (know-how) about the processes under investigation
2. Identification of problems from the chemical and process engineering point of view that have to be solved.
3. Look over of the accessible methods for problem solution (including non-radiotracer method).
4. Preparation of the experiment methodology:
   - Choice of tracers
   - Methods of experimental data acquisition and processing (hardware, software, graphical presentation of results)
5. 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.)
6. 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:

1. 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.
2. Periodically assessing the proper functioning of WWTP without it having to shut-down and for troubleshooting.
3. Planning in advance for the annual shut-down and identify the operations requiring critical improvements.
4. Periodic calibrating of pumping devices for flow rates.
5. Optimizing of equipment design and discharge for minimum adverse environmental impact.

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