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TECHNICAL NOTE

Radiotracer investigations of municipal sewage treatment stations

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Abstract Tracer techniques, which are well-established methods in process dynamics studies in industry, were applied to investigate the dynamics of sewage treatment process. The concept of residence time distribution (RTD) was used to investigate the efficiency of the primary clarifier, aeration tank and secondary clarifier of a sewage treatment plant. Preliminary treatment and modeling of the tracer data was performed using the software DTS Pro Ver. 4.20. A big short – circuiting (by-passing) with a large volume of stagnant zones were found in the primary and secondary clarifiers, while no stagnant zone was detected in the aeration tank.

Key words wastewater treatment • residence time distribution • activated sludge • radiotracer

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Introduction

Wastewater treatment is the process of cleaning used water and sewage so that they can be returned safely to our environment. Municipal discharges are one of the leading sources of water quality impairment in all waters (rivers, streams, lakes, estuaries and coastal waters). Pollutants associated with municipal discharges include nutrients, bacteria, pathogens as well as metals and toxic chemicals from industrial and commercial activities and households. The nutrients can stimulate growth of algae that deplete dissolved oxygen, which is essential for aquatic ecosystems, since most fish and other aquatic organisms "breathe" oxygen dissolved in the water column. A wastewater treatment plant removes solids, like sticks and sand, from water. It reduces organic matter and pollutants using helpful bacteria and other microorganisms, which consume organic matter in wastewater and are then separated from the water. Treatment plants then restore oxygen to the water to ensure that it can support life in the oceans, lakes, and rivers in which it is released. Biological treatment of municipal wastewater has been applied for many decades all over the world. The activated sludge process was developed in England by Arden and Lockett [1–3] and was named because it involved the production of an activated mass of microorganisms capable of stabilizing a waste aerobically.

Increasing demands for effluent quality and increasing loads in combination with shortage of land area call for an improved control and optimization of wastewater treatment plants. An improved control and optimization of the wastewater treatment plant lead to an increased pollutant removal, a reduced need for chemicals and energy savings. Applied research in radiotracer technology is an important tool in achieving an optimized plant performance. The tracer techniques can be applied in investigations like mixing studies, flow rate measurement, residence time distribution and troubleshooting of processes, thereby improving the plant efficiency. In 1953, Danckwerts [5] introduced the concept of residence time distribution (RTD). Since then it has become an important tool in the analysis of industrial units. Danckwerts showed that the RTD could be obtained by tracer methods if a tracer behaves identically with all other fluid molecules. Generally, these methods rely on tracer input in the inflow of the system under investigation and on interpreting the monitored outlet tracer response of the system. Levenspiel [7] thoroughly explained the RTD approach. He explained when it may legitimately be used, how to use it, and when it is not applicable what alternatives to turn to. Chmielewski *et al.* [4] performed radiotracer investigations of industrial wastewater equalizer-clarifiers and proposed a flow model for the system. Thýn *et al.* [10, 12] analyzed equalization of the concentration of pollutants, the process of biological activation and the settling process of sludge by means of the stimulus response method using radioisotopes as tracers. Lavenspiel and Turner [8] presented a method of interpretation of tracer experiments. Niemi [9] gave the interpretation of tracer functions under the conditions of variable flow.

The aim of this study is to analyze the flow structure in operational units of Municipal Wastewater Treatment Plant in Islamabad to improve the efficiency and economize the performance of the processes.

Methodology

The wastewater treatment plant under consideration is based on a conventional activated sludge system. The radioactive tracer ^{82}Br – with an activity of about 2 GBq – in the form of aqueous potassium bromide (KBr) was selected considering the conditions of the experiment. The following three systems of the wastewater treatment plant were investigated:

1. Primary clarifier;
2. Aeration tank (Unit 1),
3. Secondary clarifier.

The design of primary and secondary clarifiers with a scraper sludge removal is shown in Fig. 1 including indication of localization of scintillation detectors during experiments. The tracer was injected instantaneously. The four signals (input, output and two signals from detectors immersed in water, located on bridge of scraper) were registered by the multipoints measuring system Minekin 9301. The signals from rotating detectors gave possibility to establish the localization of flow stagnation zone in the clarifier volume. The step of time discretization was 1 min per channel.

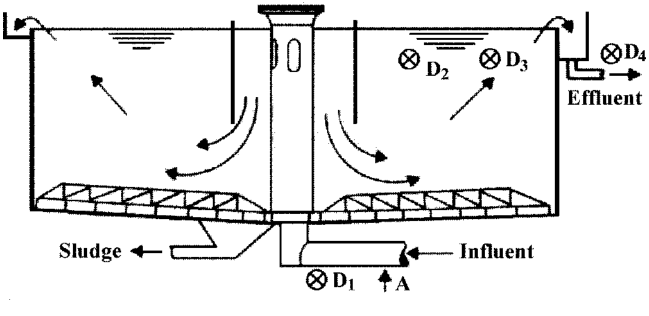

Fig. 1. Design of a circular center feed clarifier. A – tracer injection; D_1, D_2, D_3, D_4 – detectors.

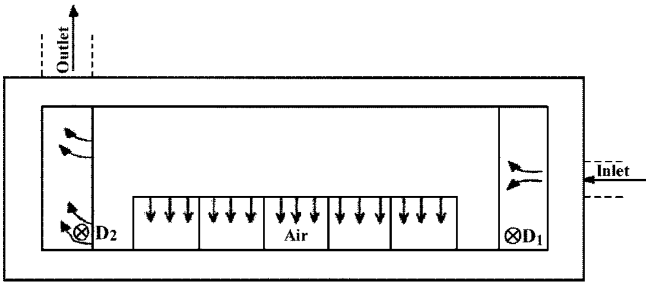

Fig. 2. Design of the aeration tank. D_1, D_2 – detectors.

The design – top view – of the aeration tank is shown in Fig. 2. It consists of five equal chambers connected by perforated baffles with nonconstrained flow near bottom and free surface. Air is feeding by perforated pipes located in the bottom region of the tank. Input and output signals were recorded. The step of time discretization was also 1 min per channel.

RTD models have been applied for industrial process investigations successfully where fluids and solids are involved. Mathematical simulation and construction of computational models are found useful. Radioactive tracers are valuable tools enabling the investigation of the physical phenomena and making it possible the identification and optimization of industrial processes. Physical and mathematical descriptions of flow, mixing characteristics of fluids or solids in systems are called the flow models. They give macroscopic, lumped sum description, which are sufficient for the majority of engineering process calculation.

In general, the selection of flow models and the determination of parameters from tracer studies is based on analyses of impulse response functions $E(t)$, which are the RTDs obtained from a tracer input to the system in the form of Dirac delta functions (instantaneous injection).

A software package DTS PRO version 4.20 that simulates dynamic models derived from RTD experiments developed by PROGEPI [6] was used for the preliminary treatment and modeling of the experimental data obtained from different units of the wastewater treatment plant. This software package can model complicated flow patterns, and model parameters can be fitted so as to fit an experimental outlet response. The composition of testing models can be made directly on screen as a graphic network by assembling and interconnecting the elementary units. The response to any entry function can be obtained at any node and at the outlet of the network.

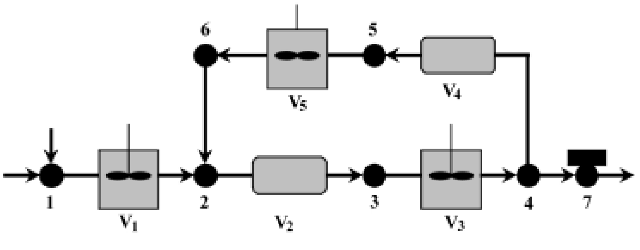

Fig. 3. Model of a primary clarifier. $V_1 = 96.2\ m^3$, $V_2 = 285.78\ m^3$, $V_3 = 201.8\ m^3$, $V_4 = 76.3\ m^3$, $V_5 = 199\ m^3$.

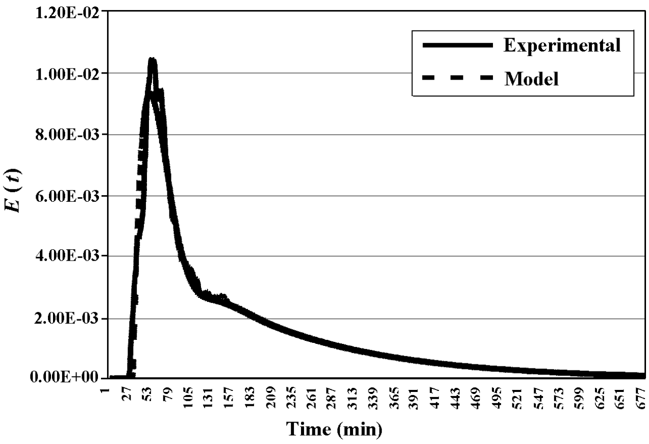

Fig. 4. Residence time distribution analysis of the primary clarifier.

Results

Primary clarifier

The volume of the circular center feed 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 as 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.

Various models with different parameters were tried for the primary clarifier [11]. The model that fits well to the experimental curve is shown in Fig. 3. In this model node no. 1 is the inlet and tracer input, node no. 7 is the outlet while V_1, V_3 and V_5 are perfect mixing cells and V_2, V_4 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. Node no. 7 is the outlet visualization node. The recycle ratio defines the relative flow rate:

$$r = \frac{Q_r}{Q_{\text{in}}}$$

where Q_{in} – input flow rate, Q_r – flow rate in the recirculation loop.

Experimental and model output response of the primary clarifier is shown in Fig. 4. It shows a large peak at 57 min and another peak appears little 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.

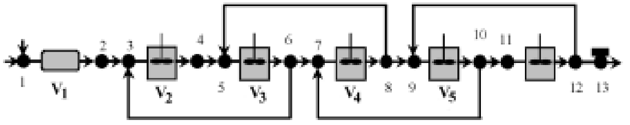

Fig. 5. Model of the aeration tank. V_1 = 80 m^3, V_2 = 101 m^3, V_3 = 100 m^3, V_4 = 100 m^3, V_5 = 97.7 m^3, V_6 = 106.7 m^3.

Aeration tank

The volume of the aeration tank (Unit 1) 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 model used for the aeration tank is shown in Fig. 5. 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 back flow ratio defines the relative flow rate:

$$b = \frac{Q_b}{Q_{\text{in}}}$$

where Q_{in} – input flow rate, Q_b – back flow rate.

Experimental and model output response of the aeration tank is shown in Fig. 6. The mean residence time of the model curve is 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 show that the aeration tank is achieving the designed residence time and is working efficiently as far as residence time is concerned.

Secondary clarifier

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

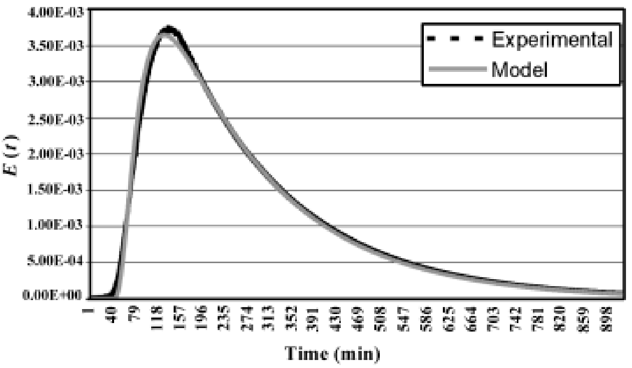

Fig. 6. Residence time distribution analysis of the aeration tank.

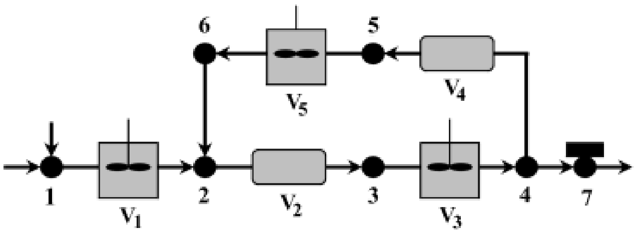

Fig. 7. Model of a secondary clarifier. $V_1 = 29\ m^3$, $V_2 = 230.2\ m^3$, $V_3 = 374\ m^3$, $V_4 = 314.1\ m^3$, $V_5 = 315\ m^3$.

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 is not taking part in the process.

The model used for the secondary clarifier is shown in Fig. 7. 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. Node no. 7 is the outlet visualization node.

Experimental and model output response of the secondary clarifier is shown in Fig. 8. It shows a large peak at 27 min showing that a major portion of the tracer passes away due to the short-circuiting causing a great 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.

In all experiments the flow rate during the first 5–6 h after tracer injection was stable. It was related with the volume of transient reservoirs and pumping system. After this time it was difficult to assure the flow stability, so the flow rate was averaged and the tail of the curve was extrapolated using the exponential function.

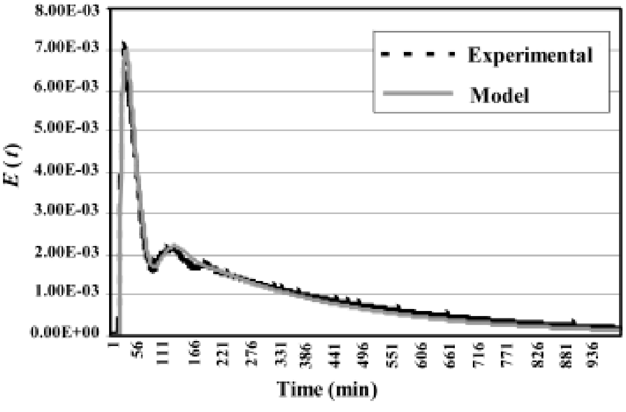

Fig. 8. Residence time distribution analysis of the secondary clarifier.

Summary

Table. Summary of the results.

		System under investigation		
		Primary clarifier	Aeration tank (Unit 1)	Secondary clarifier
Volume	(m^3)	1387	567.5	2790
Flow rate	(m^3/min)	4.8	2.08	4.16
Theoretical MRT	(min)	289	272.8	670.6
Experimental MRT	(min)	164.3	271.9	284.7
Model MRT	(min)	165.7	268.7	260.2
Dead volume	(%)	43	0.32	57.5

Conclusions

1. The radiotracer method can be successfully used to analyze the operation, to identify troubles and to improve the economic performance of the wastewater treatment plants.
2. A big short-circuiting (by-passing) with a large volume of stagnant zones was in the primary and secondary clarifiers significantly reducing their operating efficiency.
3. Almost negligible volume of the stagnant zone was detected in the aeration tank, which indicates that it is working efficiently as far as residence time is concerned.
4. The concept of residence time distribution is a powerful tool to investigate various industrial processes. Complex industrial systems can be modeled and optimum operating parameters can be obtained using software packages.

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