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DETERMINATION OF THE HYDRAULIC RESIDENCE TIME OF TRICKLING FILTERS USING RADIOTRACER EXPERIMENTS

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ABSTRACT

Trickling filters (TF) are bioreactors fulfilled with inert materials working as support for biofilm development, and have been used in a large scale in wastewater treatment for organic matter, ammonia nitrogen and nitrate removal. TF's can be widely used in Brazil, especially because of its simplicity and operational low cost. The efficiency of pollutants removal processes depends on the water flow dynamics inside the reactor. For this reason, in the present work the mean residence time of two TF's containing different support materials were determined by means of tracer testes. The radioisotope 82Br – a gamma radiation emitter, produced from soluble potassium bromide irradiated in the TRIGA reactor at the Centre for the Development of Nuclear Energy (CDTN) – was used as a pseudo-conservative tracer for the comparative study of aqueous phase flow dynamics in both TF's. Mean residence time for the first TF (containing a single support material) was 0,3 hours, much smaller than the value obtained for the second TF (containing two alternated support materials), around 2 hours. These results were already expected, once the alternated material is denser than the single one, and are very important for numerical modeling studies aiming to determine the kinetic constant for removal of the pollutants cited above.

1. INTRODUCTION

Most of Brazilian cities still discard their wastewater without any kind of treatment, causing lots of environmental damages. Disposable of wastewater containing nitrate and ammoniacal nitrogen results in oxygen depletion and eutrophication in water bodies, decrease the disinfection process efficiencies by chloride and is toxic to many aquatic species. These compounds can be removed from water by physical-chemical and biological processes, but the latter is more effective e cheaper that the former. For these reasons biofilm reactors – like trickling filters (FBP) – are widely used in wastewater treatment plants (ETE), and have a great applicability in Brazil, mainly due to its simplicity and low operational cost.

Trickling filters are bioreactors that utilize inert materials as support for biofilm growing. Those reactors are able to remove, simultaneously, organic matter, ammonium and also make available desnitrification of the wastewater, depending on biofilm heterogeneity and also the operational conditions. The efficiency of these removing processes is related to reactor hydrodynamic performance, which allow the establishment of flow behavior and detection of anomalous conditions (stagnant zones or short circuits), responsible for decreasing reactor efficiency.

Tracer tests have been used to obtain RTDs of FBPs, that allow obtaining the reactor's internal flow behavior as well as the existence of stagnant zones. Nuclear techniques provide that possibility, without the chemical analysis of a great number of samples.

The modeling of complex reactors combining hydrodynamics, transfer and kinetics aspects, which are often coupled, is one of the major challenges in chemical engineering. The first step often consists in modeling the hydrodynamics and then to take into account transfer processes and chemical kinetics. Two most different methods have been used for several years to model the hydrodynamics of reactors. The first one often called "systemic modelling" has been developed by Levenspiel. It consists in describing the flow behavior using a combination of properly interconnected elementary reactors (plug flow, perfect mixing reactor, dead volume, etc.). These models emphasize the functional aspects of the reactor and do not detail the localization of those phenomena. The initial structure is often derived from tracer experiments interpretation from which a network of elementary reactors is deduced; then, transfer and kinetics processes can be introduced. It is a global approach that has been extensively used in the past to simulate chemical reactors. It gives quite rapidly and with moderate efforts a first approximation of the reactor behaviour. These models have a good robustness in the range of experimental and size conditions for which they have been developed. However, they remain unsatisfactory when numerous local phenomena are involved and they have only limited predictability for extrapolation. For the last fifteen years, computational fluid dynamics (CFD) with chemical reaction has been more and more used to simulate the behavior of chemical reactors. This is a structural approach which discretises the reactor using a computational grid. However, despite numerous developments and improvements, this approach still remains difficult to handle for reactors involving complex and coupled local hydrodynamics, heat and mass transfer and chemical reactions because of the high computational requirements.

An instantaneous pulse of a radioactive tracer (^{82}Br) was injected in the entrance of two FBPs, objecting RTD and mixing behavior study. The trickling filters have the same characteristics, except their support material. The normalized residence time distribution data was fitted to plug flow with axial dispersion model (systemic modelling) and provided the mean residence times and the Péclet Numbers values of both filters.

2. MATERIAL AND METHODS

2.1. Study Area

The two FBP’s tested are part of the Sanitation Research and Training Center (CePTS) jointly run by the Federal University of Minas Gerais (UFMG) and the Minas Gerais Sanitation Company (COPASA), sited in the premises of the Arrudas Creek Wastewater Treatment Plant (ETE Arrudas, FIG. 1), at the northeast limits of Belo Horizonte, MG, with 19°53’42” S e 43°52’42” geographic coordinates CePTS contains several pilot units dedicated to research and development of innovative alternatives for wastewater treatment, sludge and biogas units, as well as scale-up and optimization of the dimensional and operational parameters. Besides being a platform for carrying research activities it also frequently serves educational (classes and demonstrations) and training of operators for the regional sanitation system.

Figure 1. . Aerial photo of Arrudas ETE.

2.2. Pilot Reactors

The trickling filters are 4,20 m high and their diameter is 0,76 m. They are localized at CePTS and are simultaneously fed by an up flow anaerobic sludge blanket digestion (UASB) reactor effluent. *Rotopack* e *Rotosponge* are the types of inert materials used for biofilm support that are being studied in those filters, but in filter 2 these material were alternated with polyurethane foams while in filter 1 it did not occur.

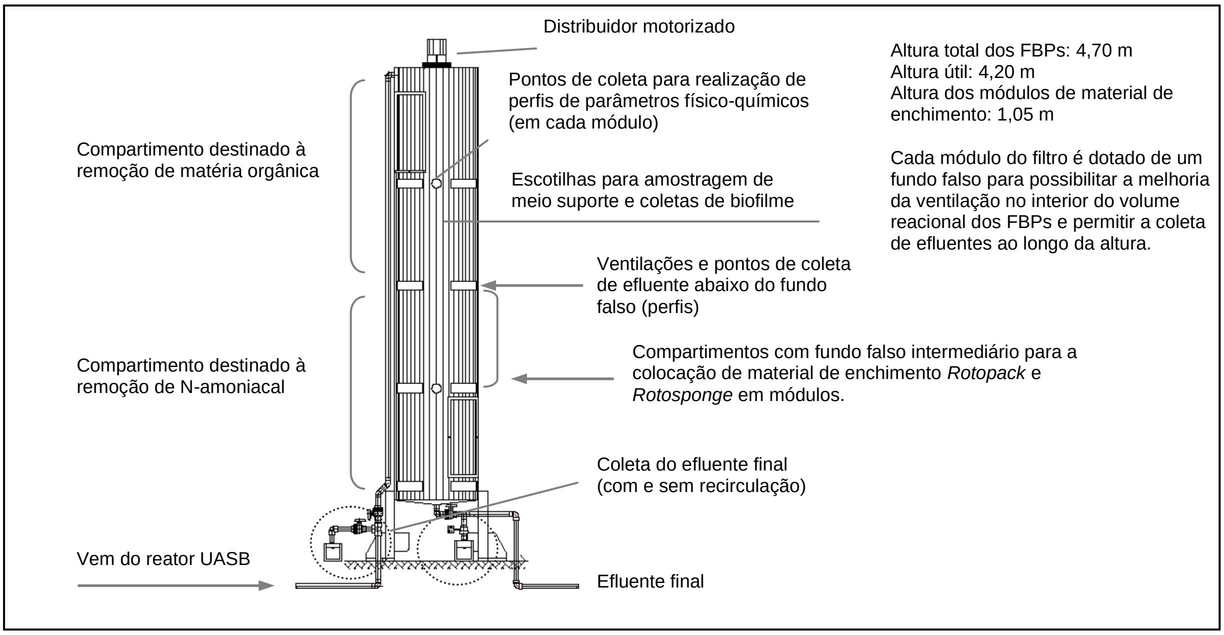


Figure 2. Trickling filters scheme.

On top of each FBP there is a motorized distributor apparatus (FIG. 3). This system was constituted by a recipient for storing wastewater coming from UASB, coupled to both a PVC pipe and to a electrical motor. PVC tube is punctured all over its length, in which wastewater goes through to reach the reactor. The electrical motor function is providing a homogeneous distribution of the wastewater in filter entrance by rotating the entire distributor apparatus.

Figure 3. Photo of motorized distributor apparatus.

Both trickling filters had worked under the same operational conditions during the tracer tests (constant flow = 6,9 m^3/d), aiming to study the influence of using polyurethane foam in the final effluent without recirculation in those systems.

2.3. Tracer Study

In the present paper the radioisotope ^{82}Br was used as a conservative tracer to study the residence time distribution in both trickling filters. This radiotracer presents many advantages: it can be easily detected outside the reactor (since it is a gamma emitter), it is highly soluble in water, it can be easily produced in research reactors and its half-life (35.3 h) is appropriate for that application.

Pressed KBr tablets (1 g each) were irradiated in the TRIGA nuclear reactor at the Center for Development of Nuclear Technology (CDTN). The tablets were left in the reactor room during a cooling down period of 48 h following irradiation to assure total decay of the nuclide ^{80}Br (4.4 h half-life) which is produced together with ^{82}Br during irradiation. The tablets were transported within lead shielding to the wastewater treatment plant (WWTP) and each one was dissolved in 500 mL of water (FIG. 3) immediately before injection to obtain the tracer solutions. The high KBr solubility in water (347 g/ml a 20°C) guarantee a fast dissolution without the need of mixing the solution – unless at the end of dissolution process, in order to get a homogeneous solution.

Figure 3. Preparation setup of tracer solutions.

The used two pressed KBr tablets presented an activity of 0,5 mCi each at moment of injection. The tracer solution was transferred to a polypropylene recipient, placed on the top of the trickling filter and surrounded by lead bricks to avoid interference in the first probe measurement (at the injection position). A peristaltic pump was used to feed the motorized distributor apparatus of the reactor with the tracer solution (FIG. 4). Both tracer solution volume and pump velocity were calculated aiming a homogeneous spread on the reactor entrance throughout one exact round of the motorized distributor apparatus.

Figure 4. Tracer injection system.

The tracer tests were planned to take place in 2 hours for filter 1 and 10 hours for filter 2. Radioisotope measurement has been done *in situ* at the FBPs exit flows counting the gamma emissions with a NaI(Tl) crystal probe. As there was no need for tracer recuperation verification (once the determination of residence time distribution is a relative measurement), utilization of these probes avoided sampling and subsequent laboratory analyses. A further advantage of using scintillation probes is related with their extremely high sensitivity for gamma radiation, which permits detection limits well below those attained by the majority of commonly utilized analytical techniques.

Taking into account that seven NaI(Tl) scintillation probes were available for experiment realization, five of them were used in the detection. They were positioned at the injection and exit point as well as at other three intermediate positions along the longitudinal axes of each trickling filter (FIG. 5), in order to collect further information on the flow characteristics inside both units. The thus minimized radiation risks were duly taken care of using standard radioprotection procedures and monitoring practices.

(a) (b)

Figure 5. Probe positions at the trickling filters.

The use of a radiotracer allowed the injection of reduced quantities of the KBr diluted in small water volumes that did not disturb neither the ingoing flow, nor the normal operational procedure of the studied FBPs. Moreover its utilization did not interfere in biochemical processes taking place inside the reactor at the time of the experiment.

The radionuclide ^{82}Br is appropriate to such application as much it does not place any risk to the environment. Considering KBr high solubility in water and its low loss due to adsorption on solid surfaces, ^{82}Br would disperse in the water flow going through the reactor. Thus, ^{82}Br concentration in the FBPs effluents can be estimated by means of the equation 1 below, not taking into account radioisotope decay (conservative hypothesis).

$Q = 6{,}90\ m^3/d = 6900\ L/d$

$$C = A/Q = 0{,}5x10^3 / 6900 = 0{,}07 \mu Ci/L = 0{,}07x10^{-3}\ \mu Ci/mL \qquad (1)$$

CNEN (1985) established 8 x 10^{-3} μCi/ml as the maximum concentration allowed to be discarded in Sewell system. Therefore, both trickling filter effluents present a concentration smaller than the permitted value.

2.4. Determination of Residence Time Distribution

After background and radioactive decay corrections, the experimental data was fitted to plug flow with axial dispersion model, a more realistic model applied in the case of flow close to plug flow and is based on the superimposition of a simple convective plug flow with an unpredictable dispersion model obeying Fick´s law. In this case, a dimensionless number, the Péclet number (*Pe*), is used as a metric of the weights of convection and dispersion in the mixed model.

The mean hydraulic residence time ($\bar{t}$) was calculated by integrating break through curves, as can be seen in equation 2.

$$\bar{t} = \frac{\int t.C(t)dt}{\int C(t)dt} \qquad (2)$$

where *C(t)* is the tracer concentration (cps) at time (t), *t* is the measuring time (d) and *d(t)* the change in time between measurements.

The Péclet number’s definition is presented in equation 3.

$$Pe = \frac{uL}{D} \qquad (3)$$

where *u* is the flow speed (m/s), *L* is the flow length (m) and *D* the radial diffusion coefficient (m^2/s).

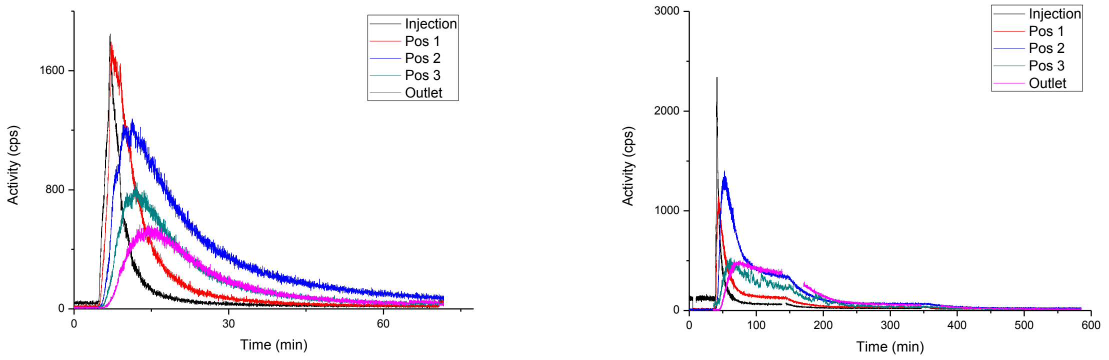
Break through curves variances (σ^2) were calculated by the method of moments, and were used for *Pe* values estimation. The relationship between *Pe* and σ^2, considering that experimental data follows plug flow with axial dispersion model, can be seen in equation 4.

$$\frac{\sigma^2}{\bar{t}^2} = 2\frac{D}{uL} - 2\left(\frac{D}{uL}\right)^2\left[1-e^{-uL/D}\right] \qquad (4)$$

3. RESULTS AND DISCUSSIONS

The tracer response curves were complete at the end of duration of the experiment These curves are obtained by a plot of the counting record at the measurement position versus the time of the counting These raw data were then corrected by subtracting the background count rate and using the decay constant to calculate the counting to a common time basis.

The tracer response curves obtained in the tracer tests in both FBPs are shown in Figure 6. Note that RTD's are those within the system volume between the entry at the top of the filter and the sections where the respective probes were positioned (and not the DTR in each of the four modules in series that make up the filter). Thus the mean residence time refers to the volume between the input and the probe sections.



(a) (b)

Figure 6. Break through curves of tracer testes: (a).Filter 1 and (b) Filter 2.

The experimental data was fitted to the plug flow with axial dispersion model (equations 2, 3 and 4) and the results of hydrodynamic parameters obtained from this adjustment are presented in table 1.

The mean hydraulic residence time ($\bar{t}$) of Filter 1 was 0,3 hours, while this same parameter of Filter 2 was 2 hours. These results are in good agreement with the expected values. Filter 2 presents a greater $\bar{t}$ than Filter 1 because of its filling material, composed by the inert material used as biofilm support and polyurethane foams together while in Filter 1 there was only inert material.

Table 1. Modelling results

Trickling filter	Probe position	Mean residence time (h)	Variance (h^2)	Péclet
1	1	0,122	0,010	2,99
	2	0,275	0,043	2,48
	3	0,257	0,036	3,22
	Outlet	0,296	0,037	4,14
2	1	1,348	2,314	0,93
	2	1,491	1,871	1,81
	3	1,793	2,048	2,47
	Outlet	1,995	1,922	3,59

Combination of inert material and polyurethane foams resulted in a denser stuff than the inert material itself, explaining the greater mean hydraulic residence time of Filter 2 compared to Filter 1.

As can be seen in Table 1, the variance found for Filter 2 curve responses (1,9 hours^2) is greater than the variance for Filter 1 (0,04 hours^2). This finding is coherent to corresponding Peclet numbers of both systems, once those parameters are correlated to each other by equation 4. The higher the peclet number is, the more the flow behavior gets closer to plug flow model, thus Filter 2 presented a bigger dispersion than Filter 1. It is also caused by the denser filling material in Filter 2.

The mean residence time measured by the probes 2 and 3 in Filter 1 were approximately equal (table 1). Plotting a graph containing only the response curves of these probes (and normalizing the curves by dividing all counts by the area under their curves, thus eliminating differences due to different sensitivities of the two probes) shows that both curves are almost coincident (FIG. 7). This indicates that the flow goes through the third module almost instantly, suggesting the incidence of a short circuit in that section, the lack of homogeneity of filling material or even the complete absence of filling material.

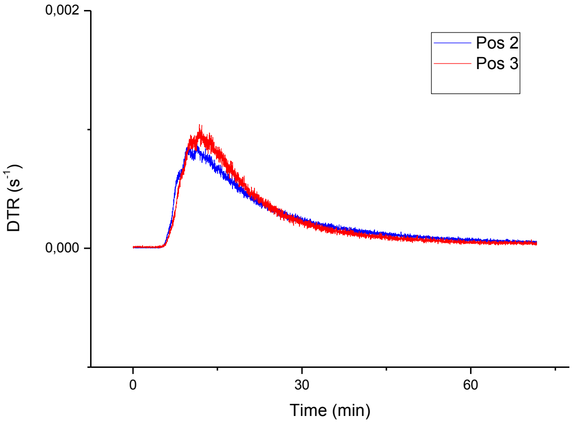


Figure 6. Normalized break through curves in positions 2 and 3 of Filter1.

The RTD plots measured in the tests and the resulting hydrodynamic parameters demonstrate that plug flow prevails in the hydraulic behavior of both units. This would be a very significant finding, given that the performance of continuous flow process units, in terms of the yield of pollutant elimination, is higher the nearest its hydraulic behavior approaches plug flow. However, the yield of pollutant elimination also depends on biofilm characteristics which, in turn, depend on the support material filling the reactor. As a consequence, the knowledge of reactor hydrodynamic behavior, in this case, is not enough to establish which reactor has the best performance. In order to get this information, the experimental data from tracer tests must be adjusted to more complex models that take into account the biofilm characteristics too.

4. CONCLUSIONS

The purpose of this study was to determine the Peclet number and the mean residence time of two trickling filters (working under the same operational conditions, but containing different filling materials), not to establish which of them presented the best performance in terms of the yield of pollutant elimination. he conclusion about the effectiveness of this equipment is a result.

Modeling the flow dynamics of reactors using radioactive tracer technique is simple and easy to apply (since tracer source and detection equipment are available), has extremely low detection limits, and provides answers where chemical tracers are not always feasible.

Far from having been exhausted, this study presented other issues, such as the existence of short-circuit in Filter 1. It is intended to proceed with data analysis and make further tests to quantify the magnitude of this effect and its influence on the reactor performance.

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