World Academy of Science, Engineering and Technology
International Journal of Environmental and Ecological Engineering
Vol:9, No:8, 2015

Investigation into the Optimum Hydraulic Loading Rate for Selected Filter Media Packed in a Continuous Upflow Filter

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***Abstract*—**Continuous upflow filters can combine the nutrient (nitrogen and phosphate) and suspended solid removal in one unit process. The contaminant removal could be achieved chemically or biologically; in both processes the filter removal efficiency depends on the interaction between the packed filter media and the influent. In this paper a residence time distribution (RTD) study was carried out to understand and compare the transfer behaviour of contaminants through a selected filter media packed in a laboratory-scale continuous up flow filter; the selected filter media are limestone and white dolomite. The experimental work was conducted by injecting a tracer (red drain dye tracer –RDD) into the filtration system and then measuring the tracer concentration at the outflow as a function of time; the tracer injection was applied at hydraulic loading rates (HLRs) (3.8 to 15.2 m h^{-1}). The results were analysed according to the cumulative distribution function F(t) to estimate the residence time of the tracer molecules inside the filter media. The mean residence time (MRT) and variance σ^2 are two moments of RTD that were calculated to compare the RTD characteristics of limestone with white dolomite. The results showed that the exit-age distribution of the tracer looks better at HLRs (3.8 to 7.6 m h^{-1}) and (3.8 m h^{-1}) for limestone and white dolomite respectively. At these HLRs the cumulative distribution function F(t) revealed that the residence time of the tracer inside the limestone was longer than in the white dolomite; whereas all the tracer took 8 minutes to leave the white dolomite at 3.8 m h^{-1}. On the other hand, the same amount of the tracer took 10 minutes to leave the limestone at the same HLR. In conclusion, the determination of the optimal level of hydraulic loading rate, which achieved the better influent distribution over the filtration system, helps to identify the applicability of the material as filter media. Further work will be applied to examine the efficiency of the limestone and white dolomite for phosphate removal by pumping a phosphate solution into the filter at HLRs (3.8 to 7.6 m h^{-1}).

***Keywords*—**Filter media, hydraulic loading rate, residence time distribution, tracer.

I. Introduction

INDUSTRIAL and municipal wastewater treatment is an essential process in the environmental protection of water bodies such as rivers, lakes and ponds.

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The wastewater treatment should be characterised as a stable, low cost and efficient process by which to achieve a good water quality that could be released into the environment without adverse effects [1]. Recently, the utilisation of active filter media to remove the contaminants from wastewater has seemed to be an attractive solution for the treatment systems [2]. In previous work [3] the capability of limestone and white dolomite for phosphate sorption was investigated. In order to assess the effectiveness and lifetime of materials that act as a phosphate eliminator, the impact of the influent retention time (RT) on phosphate sorption must be known; RT is the influent-to-media contact time [4]. In this paper the limestone and white dolomite have been packed in lab-scale filters that have an up-flow configuration, and then a tracer has been pumped into pass the filter media; the tracer has been injected into the lab-scale filters with a range of hydraulic loading rates (HLRs) to determine the optimum HLR that provides a good contact for the influent with the selected media. Loffill [5] shows that the contact time between the filter media and the water to be treated is one of the most important variables in the filtration process. Bernardez, Andrade Lima [1] states that the diffusive character of the flow passing through the filter media leads us to understand the removal process of the contaminant and it is a vital factor in the reactor modelling. The description of the hydrodynamic behaviour of the reactors is so important for design reasons, which allows us to determine parameters such as residence time.

Méndez-Romero, López-López [6] shows that the analysis of the residence time distribution (RTD) could be used in order to describe the removal processes that happen inside the filter media [7]. Examination of the flow characteristics in a reactor according to the RTD test has been widely performed.

Nemade, Dutta [8] states that the RTD is a simple and useful method to analyse flow properties, create or develop a flow mathematical model, and estimate the performance of a reactor. In the same context, Alkhaddar, Cheong [9] indicated that the residence time distribution represents a significant tool for evaluating the efficiency of a reactor.

In the case of a packed bed filter, the reacting fluid commonly does not flow uniformly through the packed media. There may be some regions in the filter media that exert a little resistance against the flow. Consequently, the influent atoms following the pathway of high resistance to flow spend much more time in the reactor in comparison with those flowing through the regions of lowest resistance to flow. This will lead to distribution of times that atoms spend in the filter in contact with the filter material.

II. Materials and Method

A. Experimental Set-up

Lab-scale filters were set up for use in this work. Each reactor included a cylinder with a diameter of 0.1 m and total volume of 0.0063 m^3; and the reactors had an up-flow configuration. The RTD is determined experimentally by injecting a tracer into the influent stream pumped into the filters by submersible pumps at some time, t = 0, and then measuring the tracer concentration, C, in the effluent stream as a function of time.

B. Tracer and Injection Method

The tracer should be chemically inert, easily detectable and soluble in the mixture [10]. Therefore a red drain tracing dye (RDD) was selected as the tracer to inject at room temperature in the lab-scale filters; the tracer concentration was 2 g/L and the injected amount was 50 ml. The out-tracer concentration was measured by HACH LANGE DR 2800 spectrophotometer device. In fact, the spectrophotometer determined the RDD absorption value at wavelength (λ = 525 nm), and then the RDD concentration was measured from the known RDD concentration calibration curve. There are, mainly, two methods of tracer injection used, called pulse input and step input. The type of tracer injection in this study was the pulse input; it allows for easy interpretation because all materials enter the reactor at once.

C. Packing Filter Media

The packing media has an essential role in the filtration process; it has an influence on the hydraulic properties and mass transfer of the contaminant. The filter media should be chemically stable, resistant to attrition, and have a high specific surface area and a low apparent specific weight [11]. The surface characteristics of the filter media can significantly affect the residence time of the influent. After an extensive literature review, limestone and white dolomite were selected for use as filter media in this work. According to a series of tests, these materials showed good physical properties such as porosity and surface area. The limestone was supplied from Omya UK Ltd and the source is Dowlow Quarry, UK; while Specialist Aggregates Ltd, UK, supplied the dolomite.

D. Analytic Method

The distribution of residence times is represented by the material exit age. In the pulse injection, a specific amount of tracer is injected into the entering filter stream in one shot. The concentration of the out tracer is then measured as a function of time. The effluent concentration–time curve is represented by the C curve in the RTD analysis. The normalised RTD function, E(t), is obtained by dividing each data point by the area under the tracer concentration curve [12]. The function E(t) has the units of time as per (1):

$$E(t) = \frac{C\,(t)}{\int_0^\infty C\,(t)dt} \quad (1)$$

The F curve is another function, which has been defined as the normalised response to a particular input. The concentration of tracer at the outlet is measured and normalised to obtain the non-dimensional cumulative distribution curve F(t), which goes from 0 to 1:

$$\mathrm{F(t)} = \frac{C\,(t)}{C\,0} \quad (2)$$

It is very common to compare RTDs by using their moments instead of trying to compare their entire distributions. The first is the mean residence time (MRT); from the measured RTD curve, the mean residence time of the reactor was determined. The mean residence time is then calculated as:

$$MRT = \int_0^\infty t\,E(t)dt \quad (3)$$

Levenspiel [13] states that the mean residence time is represented by the time (t) at which 50% of the total integral value recorded has passed. [10] Show that the theoretical mean residence time (MRT) of influent with fixed volume reactor, V, operating with a steady flow rate, Q, is given by:

$$MRT = \frac{V}{Q} \quad (4)$$

The second moment commonly used is taken about the mean and is called the variance, or square of the standard deviation. It is defined by:

$$\sigma^2 = \int_0^\infty (t - tm)^2\,E(t)dt \quad (5)$$

The magnitude of this moment is an indication of the spread of the distribution; the greater the value of this moment is, the greater a distribution's spread will be.

III. Results and Discussion

The RTD curves given in Fig. 1 were calculated from (1); they represent the results that were analysed using the moment method to obtain the optimal HLR that achieved better influent dispersion inside the selected media. It should be taken into consideration that the media depth in the rigs is 0.27 m. One of the paper's targets is to identify the contact time between the influent and the filter media. The RTD in all curves Figs. 1 (a)-(d) shows that the peak position for the tracer that passed inside the white dolomite appears early in all the applied flow rates in comparison with the peak position of the tracer in the limestone. When the flow rate increased, the time of peak appearance decreased between limestone and white dolomite. According to [14], the long tails present in the RTD curves could refer to the dead zones or stagnations. In this work, the RDD was injected as a tracer in the water stream, so the influent did not contain any impurities that create a dead zone. Consequently, no long tails appear in the RTD curves as shown in Fig. 1 and the entire tracer will be recovered. As mentioned in the work analytic method, the moments of the mean residence time (MRT) and the distribution variance, σ2, will be calculated from (3) and (5) to compare the RTD of limestone with the dolomite.

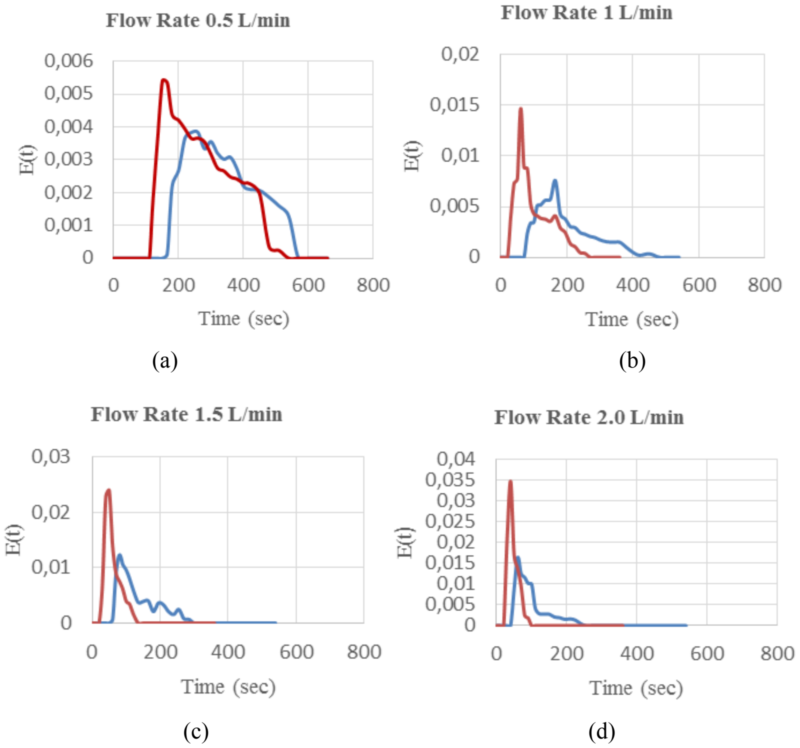

Fig. 1 RTD curve for Limestone and Dolomite at different flow rates. Limestone, Dolomite

TABLE I
PROCESS PARAMETERS AND THE EXPERIMENT'S STATISTICAL RESULTS WITH LIMESTONE AS THE FILTER MEDIA

Run No.	Filter diameter (mm)	Flow rate (L/min)	Hydraulic loading rate (m/h)	MRT (min)	σ^2 (min^2)
1	100	0.5	3.8	5.60	2.82
2	100	1	7.6	3.35	2.01
3	100	1.5	11.4	2.23	0.91
4	100	2	15.2	1.75	0.58

TABLE II
PROCESS PARAMETERS AND THE EXPERIMENT'S STATISTICAL RESULTS WITH WHITE DOLOMITE AS THE FILTER MEDIA

Run No.	Filter diameter (mm)	Flow rate (L/min)	Hydraulic loading rate (m/h)	MRT (min)	σ^2 (min^2)
1	100	0.5	3.8	4.42	2.10
2	100	1	7.6	1.69	0.80
3	100	1.5	11.4	1.00	0.14
4	100	2	15.2	0.78	0.01

Tables I and II show the values of MRT and σ^2 at each HLR for limestone and dolomite respectively. According to the σ^2 values, the tracer tends to have a good spread inside the limestone at HLRs (3.8 and 7.6 m h^{-1}), while it has a good spread inside the white dolomite at HLR (3.8 m h^{-1}). When the HLR increased more than (7.6 m h^{-1}) and (3.8 m h^{-1}) for limestone and white dolomite respectively, the magnitude of distribution variance indicates low tracer spread. The MRT values at different HLRs are in line with tracer spread results, but it is clear that the residence time of the tracer inside the limestone looks much better than that for the white dolomite.

The F curve is another function that could help to identify the material's transfer through the system. Fig. 2 shows the cumulative percentage for the tracer recovery at flow rate (0.5 L/min); the flow rate is selected according to better tracer spread and the mean residence time.

The tracer recovery for limestone and white dolomite is illustrated in Tables III and IV in more detail. It took 10 and 8 min for the tracer to totally pass through the limestone at HLRs 3.8 and 7.6 m h^{-1} respectively; this represents the better HLRs where the tracer recovery time is the longest. Large amount of the dye left the white dolomite in a short time at HLRs 7.6, 11.4 and 15.2 m h^{-1}, as shown in Table IV. Only at HLR 3.8 m h^{-1} did the tracer recovery for the white dolomite take a long time, in comparison with other HLRs.

TABLE III
THE CUMULATIVE PERCENTAGE FOR THE TRACER RECOVERY OVER RUNNING TIME FOR LIMESTONE

Run No.	Running Time 2 min	Running Time 4 min	Running Time 6 min	Running Time 8 min	Running Time 10 min
1	-	27	70	94	100
2	28	79	97	100	-
3	66	95	100	-	-
4	84	100	-	-	-

TABLE IV
THE CUMULATIVE PERCENTAGE FOR THE TRACER RECOVERY OVER RUNNING TIME FOR WHITE DOLOMITE

Run No.	Running Time 2 min	Running Time 4 min	Running Time 6 min	Running Time 8 min	Running Time 10 min
1	-	53	88	100	-
2	76	98	100	-	-
3	92	100	-	-	-
4	100	-	-	-	-

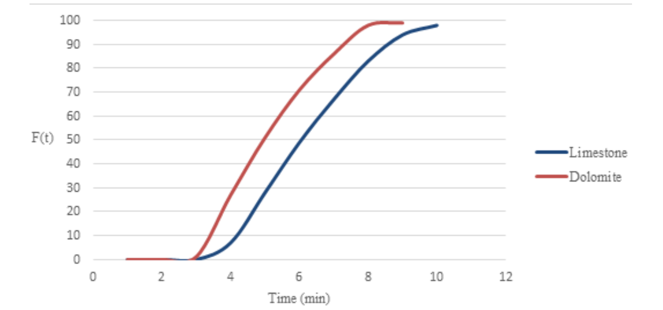

Fig. 2 The F curve for limestone and white dolomite at flow rate 0.5 L/min

IV. CONCLUSION

The average amount of time that the tracer spent in the limestone over different hydraulic loading rates was larger than for the white dolomite, so that the chance of a contaminant reacting with limestone is more than for dolomite. However, the surface reactivity of the filter media should be taken into consideration because it is a very important factor to determine the phosphate removal in addition to the contact time. Accordingly, the hydraulic loading rates of influent through the limestone for more than 7.6 m h^{-1} is unacceptable because of a large amount of material leaving the rig in a short time, while the hydraulic loading rate at 7.6 m h^{-1} and less indicated good material concentration distribution over time. In this work, the hydraulic behaviour was described for a specific configuration of continuous up flow filter that utilise the limestone and white dolomite as filter media. Consequently, these results could be a good base to understand and model the contaminant transfer when changing the filtration system dimensions.

ACKNOWLEDGMENT

The Authors thank Omya UK Ltd; for providing the limestone for this research work.

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