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Evaluation of Operation of Submerged Aerated Filters in Wastewater Treatment and Excess Sludge Production

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Abstract: The aims of this study were to evaluate the SCOD removal efficiency in submerged biological aerated filters (BAFs) and subsequently to assess the relationship between the specific surface area (S_s) and Excess Sludge Production (ESP) rate in such filters. Accordingly, four filters with different porosity and specific surface (647, 295, 175 and 136 $m^2 m^{-3}$) have been loaded with synthetic wastewater based on low fat dry milk powder with COD of 1500 mg L^{-1} in different hydraulic retention time (8, 4, 2, 1 and 0.5 h). In this study, it was shown that specific surface increase of the filters initially increases the efficiency of the filters and after a certain value, the filter efficiency remains uncharged or decreases, as in HRT of 8 h the SCOD removal efficiency of filters 1 and 2 ($S_s = 647$ $m^2 m^{-3}$ and $S_s = 295$ $m^2 m^{-3}$) were 89.8 and 91% at VOL of 3.195 and 3.727 kg COD $m^{-3} d^{-1}$, respectively. Also, the results showed that in all the filters, the production rate of suspended sludge increases inversely with the hydraulic retention time and the media with higher porosity (90.5%) produced less suspended sludge (8-57 g m^{-3}) despite having lower efficiency in the SCOD removal.

Key words: Biological Aerated Filter (BAF), wastewater treatment, excess sludge production

INTRODUCTION

Currently, the Activated Sludge Process (ASP) dominates the biological treatment of municipal wastewater (Eckenfelder and Grau, 1998; Metcalf and Eddy, 2003). Excess sludge has to be properly treated prior to final disposal, even thought the cost of sludge treatment is extremely high, accounting for up to 60% of the total operating cost in a wastewater treatment plant (Canales and Poles, 1994; Barker and Dold, 1996). The ultimate disposal of excess sludge generally includes land spreading, landfill, incineration and sea disposal (Metcalf and Eddy, 2003). It has been suggested that within the framework of sustainable development, the disposal problem may be solved by minimizing excess sludge production at the source (Roeleveld *et al*., 1997).

In this way, growth of controllable predators (Lee and Welander, 1996; Rensink and Rulkens, 1997), additional anaerobic/anoxic stages (McClintock *et al*., 1992; Barker and Dold, 1996) and ozone induced biodegradation (Yasui *et al*., 1996; Sakai *et al*., 1997) have been tested at either laboratory or pilot scale. Result show that although excess sludge production can be significantly reduced, the quality of final effluent often deteriorates due to the inherent limitations of conventional gravity clarifiers.

To overcome such limitations, application of submerged Biological Aerated Filters (BAFs) in wastewater treatment has been intensified in the recent years (Rusten, 1984; Pujol *et al*., 1992; Smith *et al*., 1992; Canler and Perret, 1994). Operating loads reported in the literature for BAF systems vary widely, BAFs with fixed bed and dense media can treat volumetric loads, approximately between 5 and 10 kg COD $m^{-3} d^{-1}$ (Pujol *et al*., 1992; Canler and Perret, 1994). Among different references, a greater disparity is found among reported hydraulic load applied in comparison to reported volumetric load applied, depending on the support material used and the particular objectives of the BAF system (Mann and Stephenson, 1997; Belgiorno and DeFeo, 2003; Xie *et al*., 2004).

For the effect of pore size of filter on the suspended solids removal efficiency, investigations have been carried out among them the work of Martin (Martin, 1996) could be referred to in which the rate of bacterial filtration has been studied.

In a theoretical study, Benthack and Bonvin (2001) tried to work out the optimum operation of bioreactors with fixed bed using numerical analysis. In this research also, the effect of specific surface of filter media on the efficiency and sludge production is not taken into account in the modeling. In some experimental researches, it has been tried to control the thickness of the biological layer (Biofilm) and prevent clogging and filter decrease of efficiency by increasing the rate of

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aeration and also adding chemical substances such as hypochlorite (Osorio and Hontoria, 2001).

Biological aerated filters, due to the nature of the treatment scheme have been invaluable help in reduction of sludge and consequently in reduction of treatment cost (Fujimoto, 1993) and also, the treatment of high strength wastewater (Westerman, 2000; Galvez *et al*., 2006). It should be mentioned that commercial types of submerged aerated filters as Biofor and Biostir have been being manufactured and used in the last 10 years in the United States (Metcalf and Eddy, 2003). However, little attention has been paid to the production rate of the suspended sludge and its relation with the physical specifications of filter.

With regard to the fact that in aerated treatment systems, the rate of sludge production is very high and it is the case for submerged biological aerated filters as well, research on the rate of suspended sludge production as excess sludge in this kind of filters looks necessary. So, in the present study, using a physical model in a pilot scale, the effect of specific surface of submerged BAF media and hydraulic retention time on the efficiency and the amount of suspended sludge production in this kind of filters was evaluated.

MATERIALS AND METHODS

Setup of biological filters: The physical model in this research was setup in the hydraulic laboratory of school of health in the town of Shiraz (Iran) on spring of 2006. The model consisted of 4 PVC pipes of 147 mm inside diameter and 1m height included the free height. Total volume of each pipe was 11.9 L. For filling the cylinders, pieces of 10, 20, 32 and 40 mm pipe with height the same as their diameters were used. The cylinders were filled with these pipe pieces up to 70 cm of their height to form the porous media of the filters. In Fig. 1, schematically, the model is shown and in Table 1, physical specifications of the model are presented.

In the model at the heights of 35 and 70 cm, from the bottom of the porous media sampling points were maintained. Aeration was done from the bottom of the cylinders by diffusers placed upside down. The amount of injected air was chosen such that oxygen would not be a limiting factor for biological growth.

For feeding the bioreactors, synthetic wastewater of 1500 mg L^{-1} COD was used which was made using low fat dry milk powder and tap water. pH fluctuation were controlled using 0.5 normal Sodium Bicarbonate. Synthetic wastewater was injected into the reactors from

Table 1: Physical specifications of the reactors

Column No.	Internal diameter (mm)	Height (cm)	[1]V_t(1)	[2]V_S(1)	[3]V_v(1)	[4]n (%)	[5]$\tau = n^{1/3}$	[6]S_s (m^2 m^{-3})
1	147	70	11.9	3.455	8.445	70.9	0.892	647
2	147	70	11.9	2.047	9.853	82.8	0.939	295
3	147	70	11.9	1.418	10.482	88.1	0.959	175
4	147	70	11.9	1.125	10.775	90.5	0.967	136

[1]Total Volume, [2]Solid Phase Volume, [3]Void Volume, [4]Porosity, [5]Totuosity, [6]Specific Surface of Filter Media

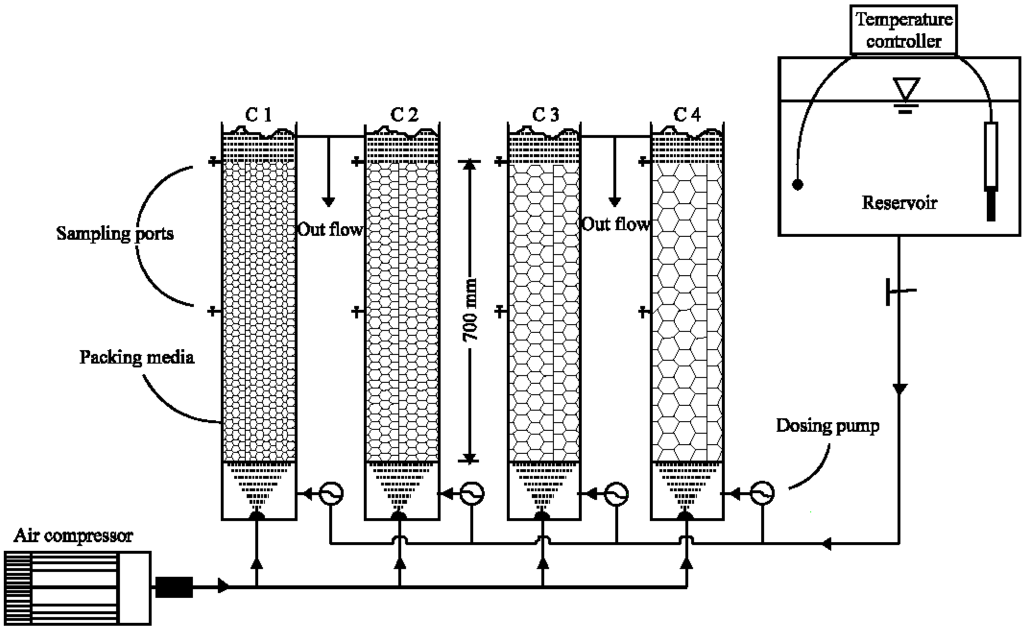

Fig. 1: Schematic figure of the physical model

bottom by dosing pumps and its temperature was controlled in the reservoir by an electric heater on 30±0.2°C. In all the phases of the experiments, the reactors were operated with upflow condition.

Startup and system operation: For operation of the system, the cylinders were filled with synthetic wastewater of 1000 mg L^{-1} COD, then, they were seeded by aerobic bacteria collected from the activated sludge system of the domestic wastewater treatment plant. Then, the air compressors were turned on and the reactors started to wok in a batch condition. The bacterial adaptation stage took about 25 days. During this time, the wastewater inside the reactors was changed 4 times and at the end of this period, thickness of the biological layer (Biofilm) in each reactor reached about 200 μm.

During this time, reduction of SCOD (Soluble Chemical Oxygen Demand) was measured daily. The result of the measurement would be presented in the corresponding section. For the study of the effect of Hydraulic Retention Time (HRT) on the efficiency of the filters, wastewater with strength of 1500 mg L^{-1} was injected into the reactors with various discharges which corresponded to different hydraulic retention times.

In all situations, 9 L min^{-1} air was compressed into the columns. In Table 2, the operation scheme of the reactors for 5 situations using discharge adjustment for setting the required hydraulic retention time is presented. After the microbial adaptation reached, the reactors stated to operate with a hydraulic retention time of 8 h and since the porosities of the reactors porous media were different, 4 dosing pumps were used separately.

Sampling at the maintained sampling points was carried out regularly and when any column reached a steady state from the viewpoints of soluble COD and outflow VSS, volume of biofilm was measured and the thickness of the biological layer in each column was estimated having the specific surface of filter media.

It should be noted that almost in all the references, among them reference (Rusten, 1984), it is confirmed that the criterion for submerged filters design is the rate of volumetric loading on the filter media and the rate of substrate removal is obtained from the hyperbolic relations such as the Eq. 1.

$$r_{COD} = r_{max} \frac{B_{COD}}{k + B_{COD}} \qquad (1)$$

In this Equation, r_{COD} is the rate of the substrate removal, r_{max} is the maximum rate of the substrate removal, B_{COD} is the organic load per unit volume of the filter and k is the constant of half velocity. All the parameters are in kg SCOD m^{-3} d^{-1}.

Table 2: Discharge of the reactors (L h^{-1})

	Column No.			
HRT (h)	1	2	3	4
8	1.056	1.232	1.310	1.347
4	2.112	2.464	2.620	2.694
2	4.224	4.928	5.240	5.388
1	8.448	9.856	10.480	10.776
0.5	16.896	19.712	20.900	21.155

Table 3: Volumetric loading of the reactors in kg SCOD m^{-3} d^{-1}

	Column No.			
HRT (h)	1	2	3	4
8	3.195	3.727	3.963	4.075
4	6.386	7.451	7.929	8.150
2	12.775	14.905	15.550	16.300
1	25.548	29.807	31.710	32.597
0.5	51.096	59.615	63.421	65.193

Table 4: Surface loading of reactors in g SCOD m^{-2} d^{-1}

	Column No.			
HRT (h)	1	2	3	4
8	4.938	12.632	22.640	29.970
4	9.871	25.254	45.298	59.941
2	19.746	50.519	90.579	119.881
1	39.488	101.028	181.158	239.740
0.5	78.976	202.055	362.316	479.481

In Table 3 and 4, the amount of surface and volumetric loadings during the experimental time are presented.

Experiments: The measured parameters in this research were SCOD, VSS, pH, DO and temperature. The first two parameters, the filter efficiency in substrate removal and excess sludge production could be obtained in any run and with a specified hydraulic retention time. pH and DO measurements were carried out randomly. These two parameters were included in the list for measurement just to be sure about proper operation of the system and stability of the reactors. The temperature of the synthetic wastewater was controlled and fixed in the reservoir on 30±0.2°C using an electric heater equipped with a sensitive electrode.

It should be noted that in the whole time of the experiments, the synthetic wastewater was not needed to be cooled. All the experiments were carried out based on the standard methods (Standard Methods, 1998).

Measurement method of the biofilm thickness: For measurement of biological layer thickness formed on porous media of the columns, the difference between the initial volume and porous volume (Vv) was divided by specific surface of each filter. It should be mentioned that at the end of each run, at the steady state, the reactors were washed using clean water in such a way that the outflow waste from the reactor would be clear and then

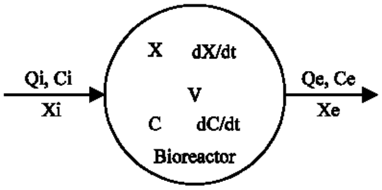

Fig. 2: Mass balance diagram

the new porosity was measured and used in the computations. It should also be noted that the water velocity for washing was kept low enough so that, the above-mentioned layer is not washed out.

Theoretical model: Before description of the experimental results, in a theoretical discussion a model is developed in which the computation of the amount of sludge production in the reactors are illustrated using the mass balance equation. In Fig. 2 the key parameters of mass balance are shown.

$$V\frac{dX}{dt} = Q_iX_i + VR_g - Q_eX_e \qquad (2)$$

$$V\frac{dC}{dt} = Q_iC_i - VR_s - Q_eC_e \qquad (3)$$

In these equations, C_i and C_e are the concentration of substrate in the bioreactor, in the inflow wastewater and in the outflow wastewater, respectively in kg SCOD m^{-3}, Q_i and Q_e are the inflow and outflow discharge of the reactors, respectively in $m^3\ d^{-1}$, V is the reactor volume in m^3, X is the biomass concentration in the reactor in kg VSS m^{-3}, X_i and X_e are biomass concentration at entrance and exit of the reactors, respectively, R_g is the net rate of bacterial growth in kg VSS $m^{-3}\ d^{-1}$, R_s is the rate of substrate consumption in kg SCOD $m^{-3}\ d^{-1}$ and t is time in day. If we assume the reactor is in a perfect mixing condition and that the discharge of waste is free of sludge or biological mass, equations 4 and 5 could written as

$$\left.\begin{array}{l} X_i = 0 \\ \frac{dc}{dt} = 0 \\ \frac{dx}{dt} = 0 \end{array}\right\} \Rightarrow \left\{\begin{array}{ll} X_e = \frac{V}{Q} R_g & (4) \\ C_e = C_i \frac{V}{Q} R_s & (5) \end{array}\right.$$

In should be kept in mind that in submerged filters X_e is the total of suspended and attached biological mass.

If we assume Y_0 is the observed yield coefficient and contains the endogenous respiration (Metcalf and eddy, 2003), relation between R_s and R_g could be written as

Table 5: Kinetic parameters and operating conditions (Xing *et al*., 2003)

Parameters	Range	Typical
K_d @ 20°C (d^{-1})	0.025-0.075	0.06
Y @ 20°C (kg VSS. kg COD^{-1})	0.25-0.40	0.40
HRT (h)	1.0-8∞	5.00
SRT (d)	0.1-8∞	30.00

$$R_g = -Y_0\, R_s \qquad (6)$$

$$Y_0 = \frac{Y}{1 + k_d.SRT} \qquad (7)$$

In the above equations, Y is the maximum yield coefficient in kg VSS kg COD^{-1}, k_d is the endogenous decay coefficient, d^{-1} and SRT is the sludge retention time, d. In the submerged aerated filters, active volume in the reactor is equal to the porous space of the filter. As a result, Based on this volume, hydraulic retention time is computed as

$$HRT = \frac{V_v}{Q} \qquad (8)$$

In Table 5, operation conditions and microbial kinetics are presented.

Sludge concentration in other systems, also, could be computed using mass balance concept. This concentration in activated sludge process and in membrane bioreactors could be obtained using the following equations, respectively.

$$X = \frac{SRT.Y(C_i - C_e)}{(1 + k_d.SRT)HRT} \qquad (9)$$

$$X = \frac{Y.SRT}{1 + k_d.SRT}\left[\frac{C_i - C_e}{HRT} + \frac{C_i - C_{sup}}{SRT}\right] \qquad (10)$$

The term C_{sup} represents the substrate concentration in sludge supernatant, kg SCOD m^{-3} and SRT is the sludge retention time, d. In both schemes (activated sludge and membrane bioreactor) Excess Sludge Production (ESP) could be calculated as (Xing *et al*., 2003)

$$ESP = \frac{V.X}{SRT} \qquad (11)$$

And by substitution of *X* from Eq. 8 and 9 in Eq. 10, ESP for activated sludge process and membrane bioreactor is obtained from the following equations, respectively.

$$ESP_{ASP} = \frac{Y.Q_i}{1 + k_d.SRT}(C_i - C_e) \qquad (12)$$

$$ESP_{MBR} = \frac{Y.Q_i}{1+k_d.SRT}\left[\frac{SRT(C_i - C_e) + HRT(C_i - C_{sup})}{HRT + SRT}\right] \quad (13)$$

As it was already mentioned, for reducing and minimizing the amount of suspended sludge in submerged filters, microbial storage capacity should be increased and the *SRT* should be increased as much as possible. So, the problem could be kept on by increasing the *SRT* to the very high values and then Eq. 9 could be written as

$$X = \lim_{SRT \to \infty} \frac{SRT.Y(C_i - C_e)}{(1+k_d.SRT).HRT} \quad (14)$$

If the limit of Eq. 14 is computed, the following equation would be obtained.

$$X = \frac{(C_i - C_e).Y}{k_d.HRT} \quad (15)$$

It is worth mentioning that from Eq. 15, for X a value is obtained, however, it does not mean that biological mass would get out of biofilter, but X, in this equation, indicates concentration of attached biological mass and is the result of dividing the mass of this biological mass by the total volume of the reactor.

RESULTS AND DISCUSSION

The most important parameters monitored in the experiments were soluble COD and VSS (Table 6-8). For brief and clearer explanation, the results of SCOD and VSS exiting from the employed biological filters in this study, versus the hydraulic retention time are presented in Table 6 and 7. It should be mentioned that the COD of the inflow wastewater in all situation was 1500 mg L^{-1}.

Returning to Eq. 1, it can be rewritten in the form of

$$\frac{1}{r_{COD}} = \frac{k}{r_{max}}.\frac{1}{B_{COD}} + \frac{1}{r_{max}} \quad (16)$$

The values of B_{COD} and r_{COD} could be obtained from the following equations.

$$B_{COD} = \frac{Q}{V}.C_i \quad (17\text{-}1)$$

$$r_{COD} = \frac{Q}{V}.(C_i - C_e) \quad (17\text{-}2)$$

Table 9 and Fig. 3 show that in all the reactors, the efficiency of the filter in removal of soluble substrate decreases with hydraulic retention time. Using equations

Table 6: SCOD exiting from the reactors in steady state (g m^{-3})

	Column No.			
HRT (h)	1	2	3	4
8	86	75	120	210
4	110	90	150	230
2	153	135	258	345
1	167	186	327	395
0.5	410	384	461	671

Table 7: VSS exiting from the reactors in steady state (g m^{-3})

	Column No.			
HRT (h)	1	2	3	4
8	6	8	3	8
4	10	16	12	17
2	25	39	17	19
1	78	55	54	28
0.5	187	126	126	57

Table 8: pH of the reactors in steady state at 30°C

	Column No.			
HRT (h)	1	2	3	4
8	7.43	7.62	7.52	7.76
4	7.40	7.51	7.44	7.80
2	7.12	7.29	7.20	6.27
1	6.91	6.79	6.83	7.34
0.5	6.79	6.81	6.80	7.21

Table 9: SCOD removal efficiency in reactors at 30°C (%)

	Column No.			
HRT (h)	1	2	3	4
8	94.3	95.0	92.0	86.0
4	92.7	94.0	90.0	84.7
2	89.8	91.0	82.8	77.0
1	88.9	87.6	78.2	73.7
0.5	72.7	74.4	69.3	55.3

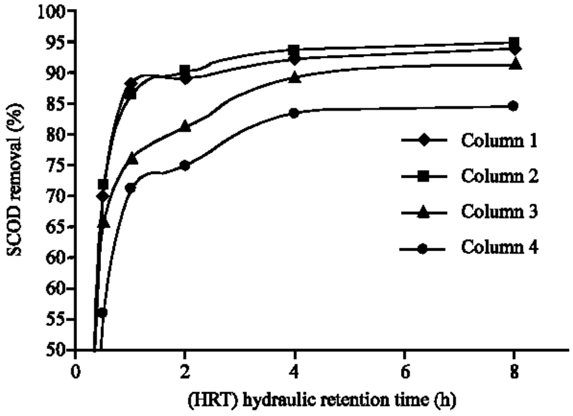

Fig. 3: Variations of SCOD percentage removal with hydraulic retention time

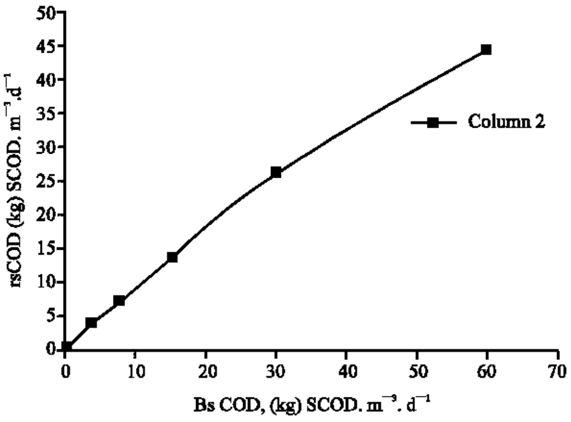

Fig. 4: Organic loading of reactor 2 in 30°C

Table 10: Volumetric load and removal of SCOD in reactors at 30°C

HRT (h)	Removal, loading (kg SCOD m^{-3} d^{-1})	Column No. 1	2	3	4
8	r_{COD}	3.013	3.540	3.5407	3.451
	B_{COD}	3.195	3.727	3.6460	4.075
4	r_{COD}	5.910	7.004	7.1361	6.903
	B_{COD}	6.386	7.451	7.9290	8.150
2	r_{COD}	11.470	13.564	13.1270	12.551
	B_{COD}	12.775	14.905	15.8550	16.300
1	r_{COD}	22.712	26.111	24.7970	24.024
	B_{COD}	25.548	29.807	31.7100	32.597
0.5	r_{COD}	37.147	44.354	43.9510	36.052
	B_{COD}	51.096	59.615	63.4210	65.199

Table 11: Coefficients k and r_{max} of the reactors in 30°C

	Column No.			
Coefficient	1	2	3	4
K, kg SCOD. $m^{-3}.d^{-1}$	204.78	246.62	147.10	123.40
$r_{max,}$kg SCOD. $m^{-3}.d^{-1}$	196.08	238.09	138.80	109.89

17-1 and 17-2 and Table 6, values of r_{COD} could be computed for various situations. These values have been presented in Table 10. By taking the Eq. 16 in a linear form, coefficients k and r_{max} could be extracted. Table 11 shows the values of these coefficients.

Substituting the values in Table 11 in Eq. 1, diagrams in Fig. 4-7 are obtained. Moreover, each filter possesses a limited ultimate strength of soluble substrate removal in volumetric loading which is independent from the hydraulic retention time. The values of this ultimate strength, r_{max}, are presented in Table 11.

In a multi-variable analysis, the relation between specific surface, porosity, temperature and pH with the efficiency of each filter could be investigated. However, in the present study, taking temperature and pH as constants, these parameters are discarded from the model for simplicity.

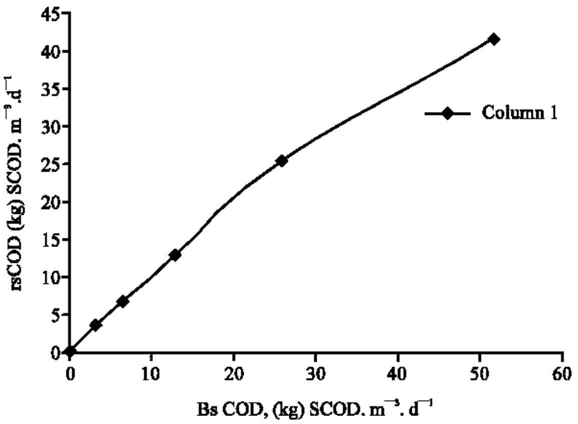

Fig. 5: Organic loading of reactor 1 in 30°C

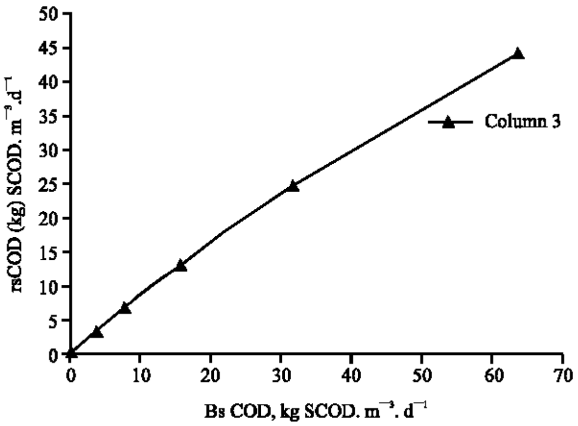

Fig. 6: Organic loading of reactor 3 in 30°C

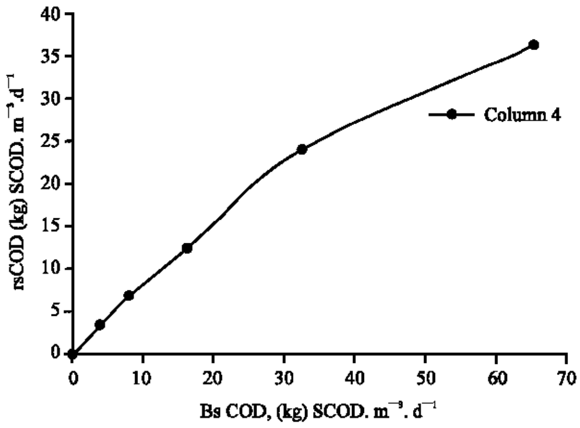

Fig. 7. Organic loading of reactor 4 in 30°C

Porosity also controls only the time-steps between two backwashes of a filter, so, in a one variable analysis, with non-linear regression models using the software Curve Expert, the best model with highest regression was selected. The exponential model has shown the highest regression in all the hydraulic retention times mentioned

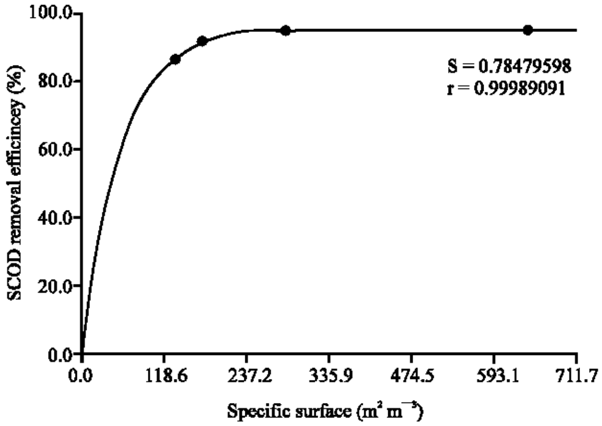

Fig. 8: Relation between specific surface and efficiency for retention time of 8 h

Table 12: Values of constants a and b in the power relation between filter specific surface and efficiency

HRT (h)	a	b
8	95.067	0.0179
4	93.661	0.0177
2	90.968	0.0139
1	97.360	0.0054
0.5	74.999	0.0115

in the previous table. The related model has a structure in the form of the following equation

$$y = \alpha.\ (1\text{-}e^{-bX}) \qquad (18)$$

In Eq. 18, x and y indicate the specific surface of the filter media in $m^2.m^{-3}$ and removal efficiency in percent, respectively and a and b are the constants of the equation. In Table 12, values of a and b are presented for specified hydraulic retention times. In Fig. 8, the exponential relation 18 has been plotted for hydraulic retention time of 8 h.

Using the graphs in Fig. 4-8, submerged aeration filters could be designed and used. Graphs in Fig. 4-7 could be used for organic loading and graph in Fig. 8 could be used for selection of specific surface of the filter media. The results in Table 7, show the outflow VSS of the reactors.

This outflow sludge is, in fact, the excess sludge, the value of which should be minimized in submerged aeration filters. Inspecting these results, the Harris model with a one-variable non-linear regression showed a good regression for the results in this table. Structure of this model is shown in the form of the following equation.

$$y = \frac{1}{a + bx^c} \qquad (19)$$

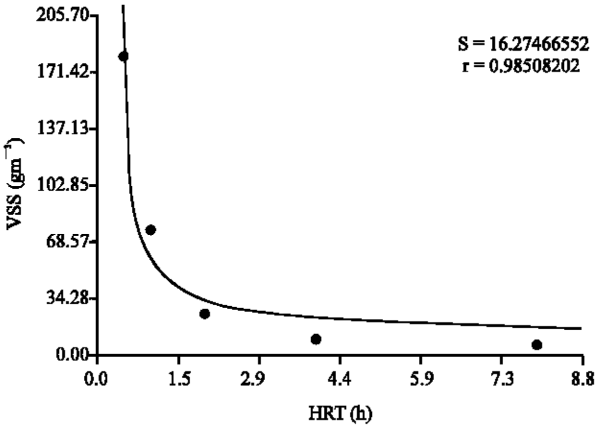

Fig. 9: Outflow VSS from reactor 1

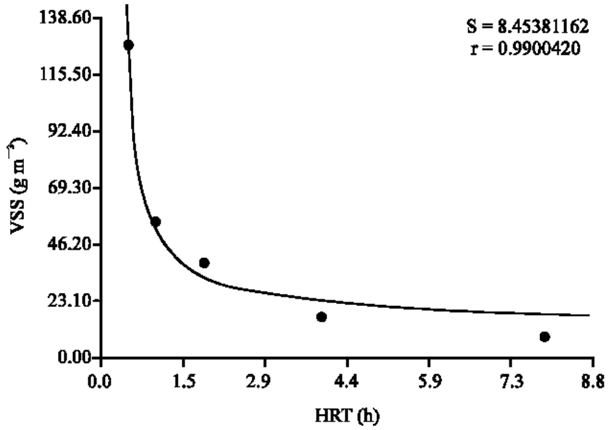

Fig. 10: Outflow VSS from reactor 2

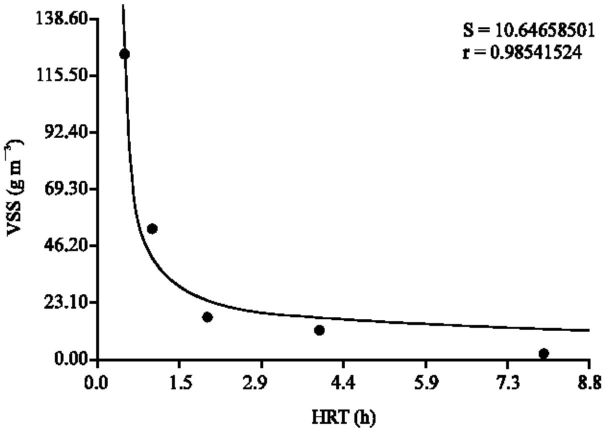

Fig. 11: Outflow VSS from reactor 3

In this Eq., x is the hydraulic retention time and y is the outflow VSS from the reactor. In Fig. 9-12 the regression of this model on the results in Table 7 is shown. As it is seen, the model shows a good regression

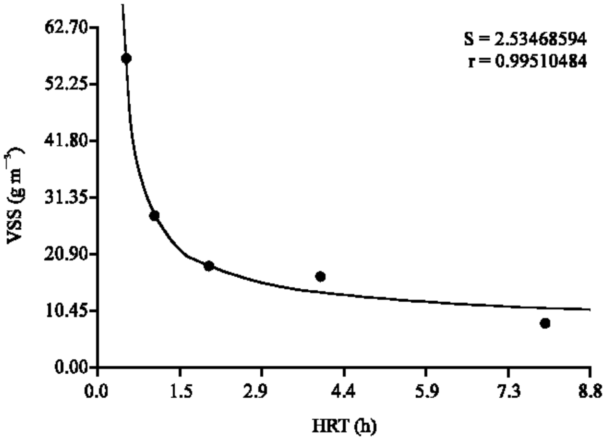

Fig. 12: Outflow VSS from reactor 4

of the observe results. So, in a reactor with a specified specific surface, the amount of outflow VSS could be estimated.

In Eq. 15, if the hydraulic retention time is inclined to infinity, the amount of outflow sludge would tend to zero and in this equation also, with a zero hydraulic retention time, the outflow sludge concentration would theoretically be infinity. Anyway, for more accurate prediction, these values would change with making parameters such as temperature a variable; however, their rates would remain constant.

CONCLUSIONS

In a general review, it could be noticed that the submerged aeration filters have very good efficiency in removal of organic substances, in low hydraulic retention times as well as in high retention times (about 1 h). Table 9 indicates the fact that increase in specific surface of porous media of the submerged biological filters helps moderately for increase in efficiency of these filters and then, the strength of the filter in removal of organic substances remains constant and it may even decrease.

It was, also, observed that the reactor No. 2 with a specific surface of 300 m^2 m^{-3} in all the situations (from the viewpoint of hydraulic retention time) is better that other ones and showed acceptable results and reactor 1 had lower efficiency compared to reactor No. 2 despite having higher specific surface. It should be noted that reactor No. 2 showed more suitable operation compared to reactor No.1 with similar loading.

On the other hand, the rate of loading on these filters compared to other treatment method was very high and reactor No. 2 showed 74.4% efficiency with loading rate of 202.05 g SCOD m^{-2} day^{-1}, while exerting such a loading had not been experienced in other experimental researches such as Xing *et al.* (2003), Osorio (Osorio and Hontoria, 2001) and Wang (Wang, 2005) works and even in some other cases loading less than this value caused failure of the proposed treatment method.

With the obtained results in section of organic substances removal, use of submerged filter No. 2 in industrial wastewater treatment, probably very strong wastewater, would be appropriate due to low required volume and high efficiency.

From the view point of excess sludge, also, as it was presented in Table 7, the highest amount of excess sludge production was related to reactor No. 1 and with hydraulic retention time of 0.5 h. The minimum amount of excess sludge production was related to reactor No. 3 with hydraulic retention time of 8 h while the minimum level of suspended solids in Wang's work has been acquired at HRT of 14 h.

Reactor No. 2 produced 55 mg L^{-1} excess sludge with hydraulic retention time of 1 h which is a proper value for organic loading of 29.807 kg SCOD m^{-3} day^{-1}.

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