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Journal of Hazardous Materials B81 (2001) 115–122

Journal of Hazardous Materials

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Pressure-drops control strategy in a fixed-bed reactor

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Received 29 March 2000; received in revised form 6 September 2000; accepted 7 September 2000

Abstract

This paper presents a strategy to control pressure-drops (head loss) in a biofilter designed according to the "Mist-Foam" concept. This concept is based on the mixing of the gaseous substrate and a liquid nutrient solution with an atomization nozzle to generate a mist passing subsequently through a synthetic polyurethane foam. In this type of bioreactor, the microbial growth reduces progressively the empty bed volume of the biofilter and causes an increase in the pressure-drops. This phenomenon can result in a complete clogging of the biofilter. The strategy of pressure-drops control presented here consists of successive interruption of the liquid flow, automatically controlled, resulting in a drying effect of the biomass. Tested during a 160 days experiment, this system has permitted to reduce and stabilize the pressure-drops in a biofilter in which the carrier exhibited a high likelihood of clogging. © 2001 Published by Elsevier Science B.V.

Keywords: Biofilter; Clogging; Biomass; Pressure-drops; Control

1. Introduction

The "Mist-Foam" concept described previously [1,2], is a concept of biofilter for gaseous substrates. It was developed to promote, as much as possible, the gaseous substrate transfer to the active biomass based on the double film theory of Lewis and Whitman [3]. This theory highlights the importance of a high gas–liquid exchange area and a thin liquid film separating the gas from the bulk liquid phase which contains the biofilm. Both considerations indicate that a bioreactor with a high carrier surface area in which the liquid presence is drastically limited should promote gaseous substrate transfer while still allowing biomass activity.

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0304-3894/01/$ – see front matter © 2001 Published by Elsevier Science B.V.
PII: S0304-3894(00)00319-8

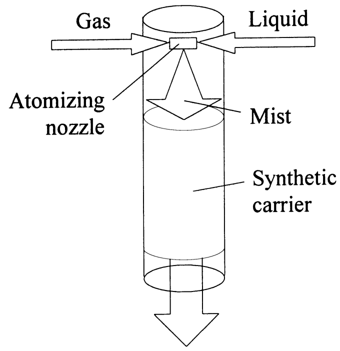

Fig. 1. The “Mist-Foam” concept.

The “Mist-Foam” concept was also developed in order to eliminate the major drawback induced by the use of classical organic carriers (e.g. peat, compost, sawdust). These organic carriers, which have been largely used in biological treatment of gases, have a high surface area and are generally operated without any liquid mobile phase [4]. Nevertheless, they are complex, degradable and entail the accumulation of potentially inhibitory reaction products in the filter-bed. On the contrary, inorganic carriers like polyurethane foam has a uniform structure and provides a high surface area for microbial development. However, such carriers require a liquid nutrient supply complementary to the gaseous substrate.

An atomizing nozzle was chosen to feed the liquid nutrient solution in accordance with the above transfer considerations. This permits the jointly injection of a very low liquid flow and the gas flow, in the form of a homogeneous mist characterized by a gas–liquid exchange area in the region of 200,000 $m^2 m^{-3}$ [2]. Additionally, a polyurethane foam presenting a defined and uniform structure was chosen as carrier. In a previous study [2], polyurethane foam was characterized as formed by slivers arranged in a regular dodecahedral structure formed by pentagons. Thus, the combination of the mist and the polyurethane foam (Fig. 1) assume the creation of a defined system presenting a uniform and high gas–liquid exchange area and allowing an active biomass growth under a drastically limited liquid presence. Previous experiments [2,5] have been carried out with a “Mist-Foam” bioreactor using methanol as model substrate. During these experiments, a volumetric methanol degradation rate of up to 1.37 $kg\,m^{-3}\,h^{-1}$ was obtained (at gas flow rate of 120 $m^3\,h^{-1}$, influent methanol concentration of 14 $g\,m^{-3}$). These results suggest that the “Mist-Foam” concept can be applicable for the treatment of a gaseous substrate. However, excessive biomass growth can be a major drawback of the system as the microbial growth reduces progressively the empty bed volume of the biofilter and causes an increase in the pressure-drops. This phenomenon earlier observed by the authors (not published) and well described previously [6–8], can result in a complete clogging of the biofilter. The applicability of the “Mist-Foam” concept or other reactor design are thus dependent on limiting the biomass growth while maintaining high microbial activity.

The clogging phenomenon is not systematically observed [5,9], but different systems have been developed recently to restrain it, either by limiting the biomass growth [6,10], by

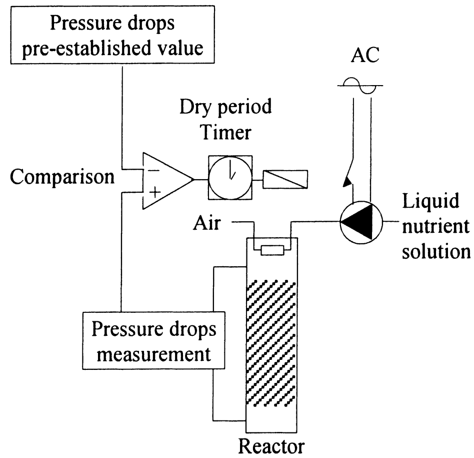

Fig. 2. The pressure-drops controller.

a regular washing of the biofilter [10] or by using predators [11]. The aim of this paper is to develop and test a system for pressure-drops control, automated by a pressure transducer. The system developed consists of a discontinuous liquid supply which combines successive dry periods (without liquid supply) and nutrient limitations, both unfavorable for biomass growth. These considerations are based on the possible effect of dry periods on water activity, which is an important factor in active biomass growth [12,13] and of the evident dependence of biomass growth on nutrient load. In order to regulate automatically the liquid nutrient supply, the pressure-drops in the reactor were chosen as the control parameter. The system using a pressure transducer (Fig. 2) permanently compares the pressure-drops in the reactor with a pre-established value. Should the pressure-drops attain the pre-established value, the liquid supply is interrupted for a programmed time, called the “dry period”, provoking a decrease of the pressure-drops. At the end of the programmed time, the liquid supply is switched on and the cycle starts again.

2. Materials and methods

To test the pressure-drops controller, two polyvinyl chloride laboratory-scale reactors (diameter: 0.11 m, height: 0.7 m) were built to contain $3.8 \times 10^{-3}\,m^3$ (diameter: 0.11 m, height: 0.4 m, in 44 slices of 9.1 mm high) of polyurethane foam (Recticel, Filtren Firend, 10 pores per inch). The foam has a specific surface area of $800\,m^2\,m^{-3}$ and an empty coefficient or porosity of 0.88 [2]. The atomizing nozzles used (#156.330.30.16 from Lechler, Fellbach, Germany) are full cone air compressed venturi effect atomizer. The mist formed by this atomizing nozzle had an arithmetic average droplet diameter of about 27 μm for a liquid and a gas flow rate of 0.5×10^{-3} and $1.2\,m^3\,h^{-1}$, respectively [2]. In order to provoke a biomass growth into the polyurethane foam, a model system was chosen. The system consisted of air as gas, biomass from an aerobic waste water treatment plant as inoculum and spent liquor from citric acid fermentation (2 g chemical oxygen demand (COD) per liter) as model nutrient solution. The biological oxygen demand (BOD_5) of the nutrient solution was estimated respirometrically at 65% of the COD value. The nutrient solution was stored in a $50 \times 10^{-3}\,m^3$ tank placed at 4°C and injected with a membrane pump (Prominent, Brussels, Belgium). The reactors were inoculated by complete immersion of the carrier for 4 days in a continuously aerated nutrient solution containing the inoculum.

During the experiment, the mist was injected in the biofilters with a gaseous and a liquid specific flow rate of 260 and $0.13\,m^3\,m^{-3}\,h^{-1}$, respectively. These values corresponded to a volumetric load of $0.26\,kg\,COD\,m^{-3}\,h^{-1}$. These figures are based on foam bed volume. The pressure-drops and the nutrient solution degradation were frequently determined while the pump working time was recorded continuously. Biomass growth in the filter-beds was determined by weighing the fresh polyurethane slices before (fresh weight) and after constant weight (TS) was attained at 105°C. By referring to the initial weight of each of the slices, the biomass and solid content of the polyurethane foam were determined and expressed as $kg\,m^{-3}$. During the discontinuous liquid supply, the weighing of the filter-bed was always made at the end of the wet periods. The BOD and the COD were determined by the standard dichromate and respirometric methods. In this paper, all results are expressed volumetrically, based on the foam bed volume.

3. Results

At the beginning of the experiment, both reactors were continuously fed with the nutrient solution. This continuous supply resulted immediately in a COD removal and an increase of the pressure-drop, both indicating biomass growth. After 65 days, the degradation rate in both reactors had reached their maximum (65% removal of the load in terms of COD) and the pressure-drops increased exponentially, demonstrating clearly the likelihood of the carrier clogging (Fig. 3). At this stage, the pressure-drops controller was set in the first reactor to a pre-established value for a linear pressure-drops of $23\,kPa\,m^{-1}$ carrier height and with an arbitrary "dry period" of 30 min. As shown in Fig. 3, the pressure-drops controller

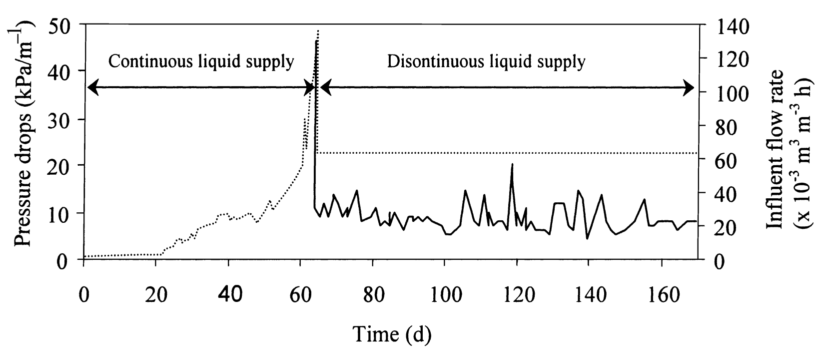

Fig. 3. Pressure-drops (---) and influent liquid flow rate (—) in reactor 1 during the experiment.

Table 1
Sludge concentration in reactor 1

Filter-bed depth (m) (the total biofilter depth was 0.4)	Biomass concentration ($kg\,m^{-3}$)		
	Day 0	Day 65	Day 125
0.05	0	460	304
0.15	0	374	459
0.25	0	288	403
0.34	0	322	362

immediately changed the pressure-drops to the pre-established value and maintained it at that value through the end of the experiment (more than 100 days).

Fig. 3 also gives the average influent liquid flow rate injected (automatically controlled by the system) which corresponds to the volumetric load. In order to set the pressure-drops in the reactor, the influent liquid flow rate was decreased by the system to approximately 25% of the initial flow rate ($32.5 \times 10^{-3}\,m^3\,m^{-3}\,h^{-1}$). This corresponded to successive dry periods of 30 min followed by wet periods of 10 min. From day 65 to approximately day 100, the influent liquid flow rate decreased continuously by ca. 0.2% per day. After this period and until the end of the experiment, the influent liquid flow stabilized at ca. 17% of the initial flow rate ($22.1 \times 10^{-3}\,m^3\,m^{-3}\,h^{-1}$, 30 min long dry periods followed by wet periods of 6 min). Due to drying, after day 100, the average effluent liquid flow rate was ca. $14 \times 10^{-3}\,m^3\,m^{-3}\,h^{-1}$ (about 40% of the influent flow rate) and was completely stopped for about 20 min during each cycle. The degradation efficiency remained constant (at about 65% removal of the influent COD and 100% BOD) throughout the experiment.

Table 1 illustrates the biomass concentration in the filter-bed just before and 60 days after the connection of the pressure-drops controller, thus at day 65 and 125, the biomass concentration changed during the experiment, increasing in the lower part and decreasing in the upper part of the reactor. From the increase of the average biomass concentration in the biofilter and by comparison of that value with the average degradation rate obtained during the related periods, it appears that the biomass build-up into the carrier was approximately 0.4 and 0.2 kg total solids kg^{-1} COD removed, respectively at the beginning and the end of the continuous liquid supply. From day 65 to day 125, during the discontinuous liquid supply, the same measure gave about 0.04 kg total solids kg^{-1} COD removed. The total solid content of the biomass present into the carrier also changed clearly. It was about 0.05 kg total solids kg^{-1} biomass throughout the continuous liquid supply period and about 0.11 kg total solids kg^{-1} biomass at day 125.

The second reactor, similarly to the first one, reached a maximum of 65% removal efficiency of the load in terms of COD after 60 days. The biomass content in the filter-bed in reactor 2 was about 420 kg biomass m^{-3} and the linear pressure-drops increased exponentially to a value of about 45 $kPa\,m^{-1}$ carrier height. At this time, the effect of dry periods of 2, 4 and 7 h was studied. The results obtained are presented in Table 2 in terms of pressure-drops and COD degradation decrease as well as the time taken, after the end of the dry period, for the reactor to regain the previous degradation and pressure-drops values.

Table 2 indicates that the duration of the dry period influences the loss of pressure-drops as well as COD degradation. Both effects are not similar because a dry period longer than 4 h

Table 2
Effect of dry period length on the pressure-drops and degradation in reactor 2

	Dry period duration (h)		
	2	4	7
Pressure-drops decrease (%)	62	80	91
Time required to recover the initial pressure-drops (h)	5	16	40
% COD degradation before dry period	65	65	65
% COD degradation after dry period	65	51	53
Time required to recover the initial degradation (h)	0	7	5

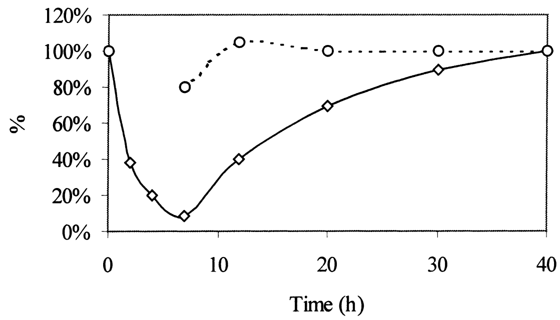

Fig. 4. Effect of a 7 h long dry period on pressure-drops (◇) and COD degradation (○) in reactor 2 (in percentage of initial values).

is needed to obtain a clear loss of the degradation rate while a dry period of 2 h was sufficient to affect substantially the pressure-drops. From this Table, it has to be also highlighted that, when a decrease of the biomass activity was observed, its recovery time was between 2 to 8 times faster than the related recovery time for pressure-drops. The effect of a 7 h dry period is also shown in Fig. 4.

4. Discussion

The results obtained here indicated that the pressure-drops in a "Mist-Foam" reactor can be set by discontinuous liquid supply, thereby avoiding any clogging risk during more than 100 days. Although from the results, no formal explanation can be proposed, one fact and two partial hypothesis can be put forward.

The fact comes from the nutrient supply limitation. As presented previously, in order to set the pressure-drops in the "Mist-Foam" reactor, the pressure-drops controller acted immediately, decreasing the nutrient liquid flow rate from 130 to $32.5 \times 10^{-3}\,m^3\,m^{-3}\,h^{-1}$. This flow rate decrease, which corresponded to a reduction of about 75% of the nutrient loading rate, could explain a slowing down of the pressure-drops increase but can not explain the successful stabilization of the pressure-drops to the pre-established value.

The first partial hypothesis comes from the physical effect of successive dry periods on the active biomass. As observed during the discontinuous liquid supply, the effluent liquid flow rate was systematically lower than the influent liquid flow rate and was stopped for 20 min during every cycle. The absence of liquid flowing trough the polyurethane foam, suggests that during these periods, a drying effect of the filter-bed was obtained. This is confirmed by the total solid concentration of the biomass which was about 0.05 kg total solids kg^{-1} biomass during the continuous liquid supply period and about 0.11 kg total solids kg^{-1} biomass during the discontinuous liquid supply period. The latter figure is twice as high as the commonly accepted value for biofilm [14] and suggests a possible decrease of water activity due to the successive dry periods. Because of the importance of such a factor for biomass growth [12,13] it is, therefore, not very surprising to have observed a decrease of about 75% of the specific biomass build-up into the carrier, expressed as kg biomass kg^{-1} COD removed. Additionally, according to Table 1, the top of the reactor showed a strong biomass loss during the discontinuous liquid supply period. Since the inlet of the reactor was subject to harsher drying conditions, the first partial hypothesis is confirmed.

The second partial hypothesis comes from the similarity of the pressure-drops controller tested to the contact-stabilization process used for aerobic wastewater treatment. The contact-stabilization process is characterized by a discontinuous contact between the active biomass and the substrate, inducing nutrient limitation which results in increased endogenous respiration and consequently, in lower biomass production, up to two times, by comparison with the more classical activated sludge process [15]. Although the contact times are greatly different, the similarity between both systems could partially explain the observed effect of discontinuous liquid supply on the biomass build-up into the carrier.

Although the system seemed to be stabilized, at the end of the experiment the biomass build-up into the carrier was not zero. This last indicates that the colonization of the carrier by biomass was still occurring. On the other hand, as demonstrated by the second reactor, the dry periods can be made longer and more effective without significant detrimental effect on the activity of the biomass.

Finally, although probable, it has still to be demonstrated that a similar behavior will be observed with a gaseous substrate containing an energy and carbon source. In a previous study [5], methanol was used as model “gaseous” substrate in a similar reactor. Albeit no significant pressure-drops were observed, impeding to experiment the effect of discontinuous liquid supply on the pressure-drops, it was observed that a dry period of up to 6 h long were applicable without significant effect on the substrate degradation rate. Consequently, the pressure-drops controller described in this paper could be an additional and effective system to prevent clogging in parallel with nutrient limitation and filter-bed washing as proposed by Smith et al. [10] and Weber and Hartmans [6].

5. Conclusion

The use of synthetic foam as a carrier for micro-organisms in a biofilter for gaseous substrate presents several advantages, such as a large surface area and a defined, inert and regular structure. On the other hand, the biomass growth in such a carrier can be a major drawback. This biomass growth reduces progressively the empty bed volume of the biofilter and causes an increase in the pressure-drops which can lead up to a complete clogging. Successive interruptions of the liquid flow results in a combined effect of dry periods and nutrient limitation. Both effects are presumably unfavorable to biomass growth and are a way of limiting the pressure-drops increase and avoiding filter-bed clogging. This system can be easily controlled by a pressure transducer. The system was tested in a model experiment using a biofilter in which the carrier exhibited a high likelihood of clogging. The pressure-drops controller allowed the reduction and the setting of the pressure-drops in the reactor during more than 100 days. Moreover, without significant modification of the biomass activity, the system developed also had a decreasing effect on the biomass growth. The system is probably applicable in other reactor types in which a clogging risk due to biomass growth may be expected.

Acknowledgements

This work was granted by the “Ministère de la Région Wallonne” in application of the “Programme de Formation et d’Impulsion à la Recherche Scientifique et Technologique (FIRST)”. The authors wish to thank Solvay S.A. and the Groupe Mouyard for their active interest and Prof. Emer Colleran, National University of Ireland (Galway), for her help in the preparation of the manuscript.

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