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Effect of liquid distribution on the organic removal in a trickle bed filter

H.D. Doan [a,*], J. Wu [a], M. Jedari Eyvazi [b]

[a] *Department of Chemical Engineering, Ryerson University, Toronto, Ontario, Canada*
[b] *School of Engineering, University of Guelph, Guelph, Ontario, Canada*

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Abstract

The effect of liquid distribution on the biological removal of propylene glycol methyl ether (PGME) in a trickle bed filter was investigated using a 0.3 m diameter column filled with 2-cm plastic spheres. Various liquid flowrates, bed heights (the ratio of bed height to bed diameter $H/D = 2.3$ and 4.6) and initial concentrations of PGME were used in experiments. The effect of initial liquid distribution was also examined using the multipoint (MPD) and single-point liquid distributors (SPD). The effect of liquid flow rate on liquid distribution, and hence, the BOD_5 removal was found more significant for the short bed ($H/D = 2.3$). The BOD_5 removal using MPD increased about 29% when the liquid flow rate was increased from 0.184 to 0.918 kg m^{-2} s^{-1}. On the other hand, for $H/D = 4.6$ with both MPD and SPD, the effect of liquid flowrate on the BOD_5 removal was insignificant although the dynamic liquid hold-up increased about two fold. It was also found that local distribution of the BOD_5 removal corresponded well with local liquid distribution in the bed. In addition, a 37% decrease in the percentage BOD_5 removal was observed while the BOD_5 removal amount increased from 62 to 211 mg L^{-1} with increases in the initial concentration from 100 to 500 ppm. Based on the Monod kinetic model, the maximum BOD_5 removal rate in the trickle bed filter was found to be 11.7 mg L^{-1} h^{-1} and the Monod constant was 759 mg L^{-1}.
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Keywords: Trickle bed filter; Liquid distribution; Liquid hold-up; BOD_5; Rate constant

1. Introduction

In a trickle bed filter, microorganisms in the biofilm, which is attached on the packing surface, consume biodegradable organics in the wastewater flowing down the bed. Therefore, the organic removal depends on the amount of microorganisms in the bed and the contact of the wastewater to the biofilm. The average contact time of liquid with microorganisms is a function of the hydraulic loading rate and the depth of the packed bed [1].

The performance of a trickle bed reactor highly relies on the uniformity of liquid distribution throughout the bed. Liquid distribution critically affects mass and heat transfer efficiency and thus the overall reactor performance. In a catalytic reactor liquid maldistribution caused non-uniform wetting of catalyst particles, which in turn reduced the contact between liquid and catalyst leading to an inefficient catalyst usage [2,3].

Good liquid distribution throughout the trickle bed filter is essential for the full utilization of the bed capacity. However, because of liquid maldistribution a portion of the packing in the bed remains dry. Non-wetted zones in the bed are not colonized by the micro-organisms rendering a low efficiency of the trickle bed filter. In addition, good liquid distribution minimizes plugging and sloughing problem and liquid channeling [4].

The flow pattern in a trickle bed filter is rather complicated and affected by liquid flow rate, packing configuration, liquid distributor design, and packing height. A number of studies have been done on liquid distribution in a packed column. Several researchers have also measured the efficiency of the biological oxygen demand (BOD) removal in a trickle bed filter under different operating conditions [5,6]. However, little attempt was done to relate the effect of liquid distribution to the removal of the BOD of wastewater in a trickle bed filter although numerous studies on the removal of contaminants in air using a trickle bed air biofilter have been reported, such as a recent investigation of hydrodynamics in a trickle bed air biofilter and its effect on the removal of xylene isomers by Trejo-Aguilar et al. [7]. Only Crine et al. studied the effect of the liquid flow distribution on

* Corresponding author at: 350 Victoria Street, Toronto, Ontario, Canada M5B 2K3. Tel.: +1 416 979 5000x6341; fax: +1 416 979 5083.
E-mail address: hdoan@ryerson.ca (H.D. Doan).

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Nomenclature

a	specific are of the packing in the trickle bed filter ($m^2\ m^{-3}$)
a_h	hydraulic specific area of the packing ($m^2\ m^{-3}$)
BOD_5	5-day biochemical oxygen demand ($mg\ L^{-1}$)
C_i	BOD_5 concentration in liquid ($mg\ L^{-1}$)
C_h	packing constant
COD	chemical oxygen demand ($mg\ L^{-1}$)
d_p	particle diameter (m)
D	trickle bed diameter (m)
Fr	the Froude number ($Fr = [u^2\ a]/g$)
g	gravitational acceleration ($9.18\ m\ s^{-2}$)
h_d	dynamic liquid hold-up ($m^3\ m^{-3}$)
H	trickle bed height (m)
K_i	Monod constant ($mg\ L^{-1}$)
MC	liquid distribution coefficient
n	number of liquid collecting cells in the collector
Q_i	liquid flow rate to an individual liquid collecting cell ($m^3\ s^{-1}$)
Q_{av}	averaged liquid flow rate to a liquid collecting cell ($m^3\ s^{-1}$)
r_i	BOD_5 removal rate in the trickle bed ($mg\ L^{-1}\ h^{-1}$)
r_{max}	maximum BOD_5 removal rate in the trickle bed ($mg\ L^{-1}\ h^{-1}$)
Re	the particle Reynolds number ($Re = [d_p\ \rho\ u]/\mu$)
u	Liquid superficial velocity in the trickle bed filter [$m\ s^{-1}$]
V_d	volume of drained liquid from the trickle bed filter (m^3)
V_r	volume of the trickle bed filter (m^3)

Greek letters

μ	liquid viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	liquid density ($kg\ m^{-3}$)

the overall removal rate of the organic matter in a trickle bed filter in the early nineties [8]. Therefore, in the present study, the influence of liquid distribution on the BOD removal was examined with a focus on local liquid distribution and local BOD removal in the trickle bed. The effect of liquid flowrate and bed height on liquid distribution and dynamic liquid hold-up was also determined. Under various liquid distribution and liquid hold-up conditions, the removal of the organic matter was evaluated. Kinetic models for the removal of PGME in the trickle bed filter were also developed.

2. Experimental methodology

A 0.3-m diameter PVC column filled with 2-cm plastic spheres was used as a trickle bed filter in the present study (Fig. 1). Packing heights of 0.7 m and 1.4 m were used. These bed heights are equivalent to the ratio of bed height to bed diameter H/D of 2.3 and 4.6. The column was opened at the top to allow natural air draft.

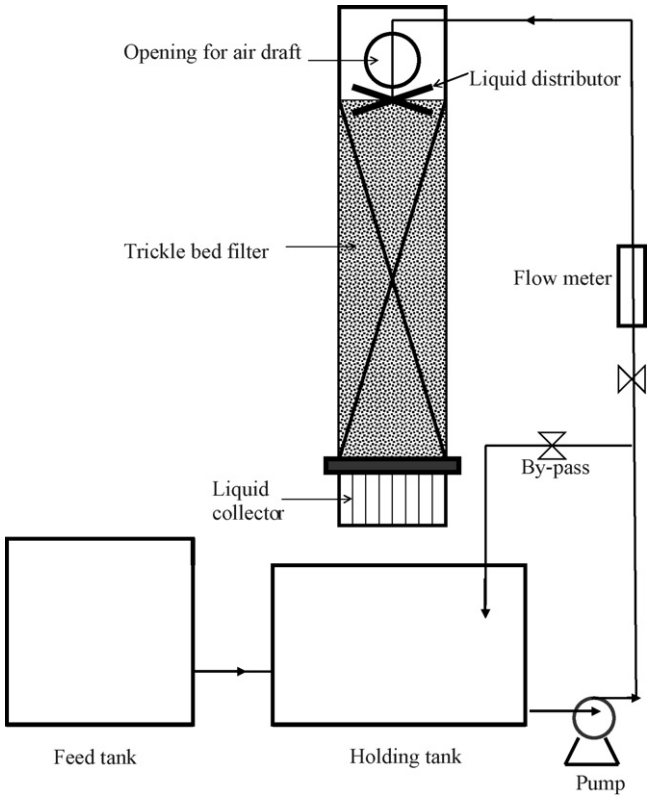

Fig. 1. Schematic diagram of the experimental apparatus.

Water was pumped from a 350-L feed tank to a liquid distributor at the top of the packed bed. Liquid flow rates of 0.184, 0.376, 0.551, 0.734, and 0.918 $kg\ m^{-2}\ s^{-1}$ were used. A rotameter (Blue-White F-450, Fabco Inc., Vaughan, Ontario) was used to monitor liquid flow rate. Two types of liquid distributors were used in the present study: a single-delivery-point distributor (SPD) and a 25-delivery-point liquid distributor (MPD). The single-point liquid distributor (equivalent to 14 nozzles m^{-2}) was a vertical tube with a 1.5-cm diameter opening, whereas the 25-delivery-point distributor (equivalent to 354 nozzles m^{-2}) was a cross type distributor (MPD) with six liquid delivery points in each of the four arms and one liquid delivery point on the intersection of arms. The diameter of the liquid delivery nozzles was 0.3 cm. It is relevant to mention that the recommended liquid-delivery-nozzle density was 65–100 m^{-2} for an adequate initial liquid distribution at the top of a packed bed [9,10].

A liquid collector was installed at the bottom of the column below the packing support. This was used to measure liquid flow distribution in the packed bed. The liquid collector had 37 collecting cells arranged in such a way that local liquid flow data were obtained not only over the cross-sectional area of the bed, but also at various diagonal and concentric paths as shown in Fig. 2 . Each collecting cell was a 15-cm height cylinder with a diameter of 3.5 cm. The bottom of each collecting cell was connected with a drain tube for liquid volume measurement.

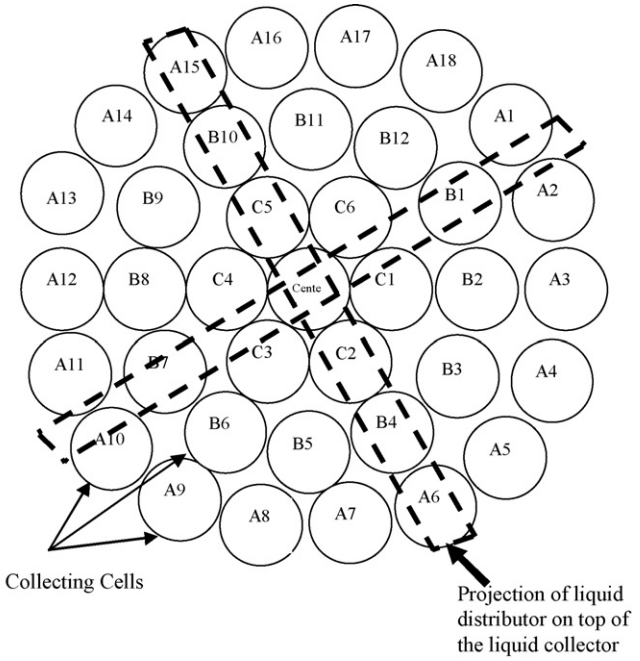

Fig. 2. Lay-out of liquid collecting cells in the liquid collector.

Liquid distribution is usually quantified by a liquid distribution coefficient defined as:

$$\mathrm{MC} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{Q_i - Q_{\mathrm{av}}}{Q_{\mathrm{av}}}\right)^2} \quad (1)$$

where n is the number of liquid collecting cells, Q_i is the liquid flow to an individual cell and Q_{av} is the averaged value of all measured liquid flows to individual cells.

Dynamic liquid hold-up was also measured using the draining method [11]. The liquid inflow was stopped when a stable hydrodynamic condition in the bed was achieved. Subsequently, the liquid was drained for a period of 30 min and its volume was measured. The dynamic liquid hold-up (h_{d}) was then calculated using the following equation:

$$h_{\mathrm{d}} = \frac{V_{\mathrm{d}}}{V_{\mathrm{r}}} \quad (2)$$

where V_{d} is the volume of the drained liquid, and V_{r} is the volume of the bed.

In the second phase of the present study, the organic removal in the trickle bed filter was investigated. A start-up period was required for the microorganism to grow and build up on the surface of the packing particles and acclimate to propylene glycol methyl ether (PGME). At the beginning, the trickle bed filter was inoculated with Polyseed® (InterBio Inc., Texas) and run in a batch-recirculation mode for 6 weeks. During this period, the trickle bed was fed with glucose solution (500 mg L^{-1}). Ammonium chloride [NH_4Cl] (105 mg L^{-1}) and disodium hydrogen phosphate heptahydrate [$Na_2HPO_4{\cdot}7H_2O$] (47.5 mg L^{-1}) were added to the feed solution as nitrogen and phosphorous sources. The chemical oxygen demand (COD) concentration of the feed was increased in four steps of 3-day intervals, from an initial concentration of 70 mg L^{-1} to a final of 550 mg L^{-1}. Water samples were taken daily from the holding tank. The pH and the 5-day biological oxygen demand (BOD_5) of the samples, as indicators of the biological activity, were measured. The pH of the solution in the holding tank decreased gradually due to the metabolic products generated by the biomass in the column. In order to maintain the pH at 7, an appropriate amount of 0.1 M sodium hydroxide solution was added to the wastewater. The BOD_5 of the solution decreased with time, which was the evidence of biological activity and growth.

After the start-up period a substantial amount of biomass on the packing surface was observed. The microorganisms were then progressively adapted to PGME by increasing its concentration in the feed solution gradually in increments of 100 mg L^{-1} while the glucose concentration was decreased appropriately to maintain the total COD at 550 mg L^{-1}. Samples were taken each time before and after adding the mixture of PGME and glucose for measurements of BOD_5. Continuous reduction in the measured BOD_5 showed that the acclimation was progressing steadily. The adaptation process continued over a period of about 2 weeks until the feed solution only contained PGME. The experiments were then started.

The effect of liquid flow rate, packing height and liquid distributor design on the removal of PGME was examined. In addition, the effect of the organic loading (initial organic concentration) on the BOD removal in a trickle bed filter was investigated using five initial PGME concentrations of 100, 200, 300, 400 and 500 ppm.

Water samples were taken daily from the liquid holding tank over a period of 4 days for each run. The BOD_5 and the COD of the samples were measured using the standard methods 5210 and 5220, respectively [12]. To investigate the effect of liquid distribution on the local organic removal, water samples were also taken from the collecting cells in the liquid collector while the trickle bed filter was operated under a continuous mode. The cells located in two diagonal paths of the bed cross-sectional area were selected for water samplings, of which the COD and BOD_5 were measured, so that the radial profiles of the BOD_5 and the COD were obtained.

3. Results and discussion

3.1. Liquid distribution and dynamic liquid hold-up

The variation of the liquid distribution coefficient, MC, with liquid flow rate for both the multipoint liquid distributor (MPD) and the single point liquid distributor (SPD) is presented in Fig. 3 . For MPD with the bed height of 1.4 m ($H/D = 4.6$), the liquid distribution coefficient only decreased slightly with increases in the liquid flow rate from 0.184 to 0.918 kg m^{-2} s^{-1}. Other authors also observed a similar trend of the MC with liquid flow rate in a packed bed [13]. On the other hand, the MC value with SPD appeared to increase with liquid flow rate. When the liquid flow rate was increased, liquid flow concentrated primarily in the central area of the column. Therefore, highly non-uniform liquid distribution at the bed exit led to the high MC values at higher liquid flow rates. In addition, as shown in Fig. 3, the MC

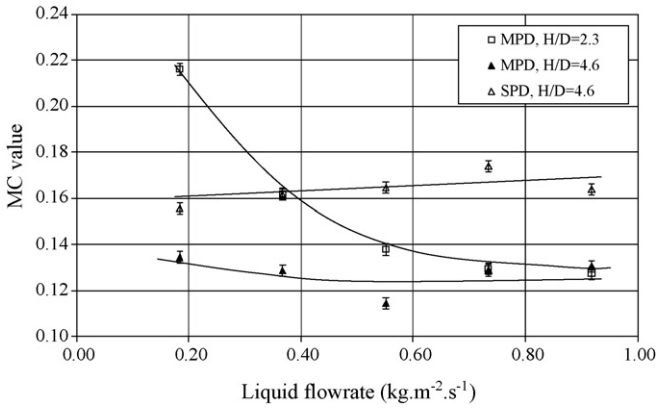

Fig. 3. Effect of bed height on liquid distribution at various liquid flowrates.

values with MPD were significantly less than those with SPD due to a more uniform initial liquid distribution provided by MPD at the top of the trickle bed.

Fig. 3 also shows the effect of the bed height on liquid distribution. For the short bed of 0.7 m high ($H/D = 2.3$), no wall flow was observed at all liquid flow rates used in the present study. This is in agreement with our previous study and other authors' investigation that showed the occurrence of the wall flow at $H/D > 4.0$ [14]. The MC value also decreased significantly when liquid flow rate was increased from 0.184 to 0.551 kg m^{-2} s^{-1}. At low flow rates of 0.184 kg m^{-2} s^{-1} and 0.376 kg m^{-2} s^{-1}, liquid spreading was low resulting in higher MC values. As the liquid flow rate was increased, higher impact momentum of liquid streams to the packing helped spreading out liquid more, leading to better liquid distribution and lower MC values. In addition, the MC value for the short bed approaches that of the tall bed ($H/D = 4.6$) at high liquid flow rates (0.734 kg m^{-2} s^{-1} and 0.918 kg m^{-2} s^{-1}). This indicates that at low liquid flow rates, extra packing is needed for the liquid distribution to reach a steady condition. The result obtained in the present study is in agreement with the findings of other authors who reported that the bed height required for the liquid to reach its fully developed state was reduced with increases in the liquid flow rate [15].

The contact between the liquid and the packing in a trickle bed is related to the liquid hold-up [16,17]. Wetting of the packing in turn affects the efficiency of the trickle bed filter. Therefore, the dynamic liquid hold-up was measured at varied liquid flow rates from 0.184 to 0.918 kg m^{-2} s^{-1}. The dynamic liquid hold-up increased with liquid flow rate for both types of liquid distributors, as expected (Fig. 4). The dynamic liquid hold-up is usually considered including liquid films and rivulets. The relative amount of these elements changes with liquid flow rate. At low liquid flow rates, the liquid hold-up is mainly of liquid films and a small number of rivulets. As the liquid flow rate is increased, the number of rivulets and their sizes increase leading to an increase in the liquid hold-up [18–20].

The liquid hold-up in a packed bed can be expressed as [16]:

$$h_L = \left(12\frac{Fr}{Re}\right)^{1/3}\left(\frac{a_h}{a}\right)^{2/3} \quad (3)$$

where a_h is the hydraulic (wetted) specific area and a is the (physical) specific area of the packing or particles in the bed, Re is the particle Reynolds number and Fr is the Froude number.

The relationship of a_h and a can be written as:

$$\frac{a_h}{a} = C_h Re0.15\, Fr0.1 \text{ for } Re \langle 5 \quad (4)$$

where C_h is a constant that is packing specific, e.g. for 25-mm metal Pall rings, $C_h = 0.719$.

By combining Eqs. (3) and (4), one can see that the dynamic liquid hold-up is proportional to the liquid flow rate to a power of 0.57. For both MPD and SPD as shown in Fig. 4, the dynamic liquid hold-up was found to be proportional to the liquid flow rate to a power of 0.46, which is somewhat comparable to that from the correlations proposed by Billet and Schultes [16]. It is worthy to note that the correlations given in Eqs. (3) and (4) were developed from the data of different types of random packing where the bed porosity was in the order of 0.90. On the other hand, the porosity of the trickle bed with spheres used in the present study was in the order of 0.45. Therefore, the dynamic liquid hold-up in a packed bed of random packing tends to be higher than that of a bed of spheres, especially at high liquid flow rates; hence, it would be more dependent on the liquid flow rate as indicated by its proportionality to a higher power of the Reynolds number.

Fig. 4 also shows that the dynamic liquid hold-up was significant higher with MPD. Lower liquid hold-up with SPD might be due to poorer liquid distribution attained with this distributor. This was reflected by higher MC values for SPD as previously shown in Fig. 3. It is also relevant to note that on the average, the dynamic liquid hold-up increased about 20% with the presence of the biofilm on the packing as shown in Fig. 4. The biomass on the packing surface might enhance the wettability of the packing (plastic spheres) and create regions in the trickle bed where liquid was retained loosely and drained off when the dynamic liquid hold-up was measured. Therefore, an increase in the dynamic liquid hold-up with the presence of the biomass in the trickle bed was observed. This is in agreement with the result obtained by Trejo-Aguilar et al. [7]. The authors reported increases in the

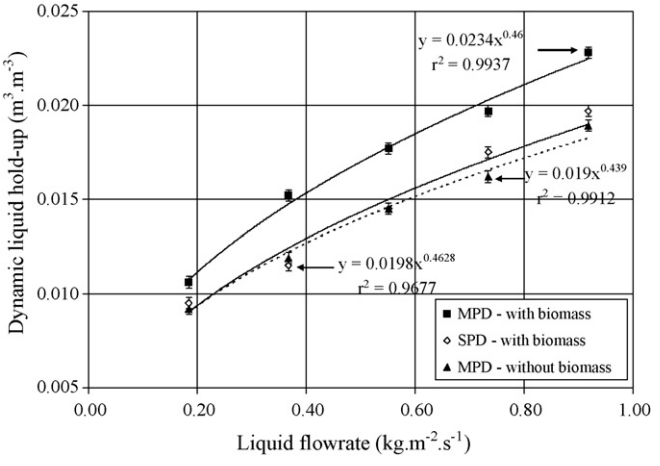

Fig. 4. Effect of liquid distributor design on dynamic liquid hold-up with $H/D = 4.6$.

dynamic liquid hold-up with decreasing bed porosity from 0.95 to 0.41 due to the build-up of the biomass in the bed.

3.2. Biological treatment of propylene glycol methyl ether (PGME)

3.2.1. PGME removal kinetics

The Monod equation is commonly used to describe the kinetics of biodegradation of organic materials; hence, it was adopted to fit the experimental data in the present study. From the experimental BOD_5 removal rates obtained at different organic concentrations, the kinetics of the BOD_5 removal in a tricked bed filter can be modeled using the Monod equation as below [21,22]:

$$r_i = \frac{r_{\max} C_i}{K_i + C_i} \tag{5}$$

where C_i is the BOD_5 concentration in simulated wastewater, K_i is the Monod constant, r_i is the BOD_5 removal rate and $r_{\max}$ is the maximum BOD_5 removal rate.

Eq. (5) can be rewritten as:

$$\frac{C_i}{r_i} = \frac{K_i}{r_{\max}} + \frac{C_i}{r_{\max}} \tag{6}$$

Eq. (6) indicates that the maximum BOD_5 removal rate, $r_{\max}$, and the Monod constant, K_i, can be determined from a linear plot of C_i/r_i versus C_i as shown in Fig. 5 . From the slope of the line and its intercept with the vertical abscissa as shown by the correlation obtained from linear regression ($r^2 = 0.987$) in Fig. 5, the maximum BOD_5 removal rate was found to be 11.7 mg L^{-1} h^{-1} and the Monod constant was 759 mg L^{-1}, respectively.

3.2.2. Effect of initial concentration

Initial PGME concentrations of 100, 200, 300, 400, and 500 ppm were used to examine the effect of the initial concentration on the PGME degradation rate in a trickle bed filter. The liquid flow rate of 0.551 kg m^{-2} s^{-1} was used. The amount of BOD_5 removed after 72 h of treatment was found to increase with the initial concentration as shown in Fig. 6 . A similar trend was observed by Atkinson and Abdel Rahman Ali in their investigation of the removal of glucose in a trickle bed filter with liquid flow rates from 0.16 to 1.08 kg m^{-2} s^{-1} [23]. As can be seen in Fig. 6, the variation of the amount of BOD_5 removed with the initial PGME concentration appears to have two regions with the transition point at the initial concentration of 300 ppm. For the initial concentrations from 100 to 300 ppm, the amount of BOD_5 removed increased sharply with the solute concentration. At low concentrations, the organic concentration gradient between the bulk liquid and the biofilm, which was the driving force for mass transfer from the bulk liquid to the biofilm, was small; hence, the mass transfer rate from the bulk liquid to the biofilm was low. Therefore, the overall organic removal process might be predominantly mass-transfer controlled. The BOD_5 removal would thus increase substantially with mass transfer enhancement by concentration increases. On the other hand, at higher organic concentrations of 400 ppm and 500 ppm, the increase in the amount of BOD_5 removed became moderate. The concentration gradient between the bulk liquid and the biofilm was larger. The mass transfer rate of the substrate to the biofilm was higher. The organic removal rate might thus be predominantly controlled by the rate of biodegradation of the organic matter at the biofilm. Consequently, the amount of BOD_5 removed would be less dependent on the organic concentration in the bulk liquid. On the overall, the amount of BOD_5 removed increased about 3.4 times from 62 to 211 mg L^{-1} with increases in the initial PGME concentration from 100 to 500 ppm.

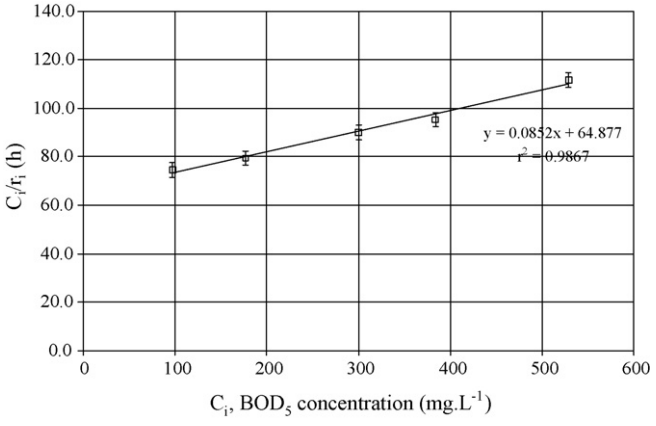

Fig. 5. Monod model for the BOD_5 removal kinetics at liquid rate of 0.551 kg m^{-2} s^{-1} with MPD and $H/D = 4.6$.

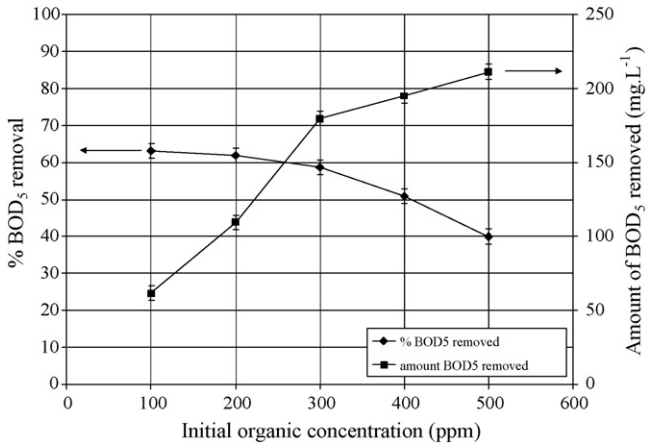

Fig. 6. Effect of initial concentration on the organic removal over 72 h of treatment at liquid rate of 0.551 kg m^{-2} s^{-1} using MPD and $H/D = 4.6$.

Although larger amounts of PGME were removed at higher initial PGME concentrations, the percentage BOD_5 removal decreased with increases in the initial concentration, as expected. Similar trends were also obtained for the amount COD removed and the percentage COD removal. Similar observations were reported in the literature [24,25]. The organic removal rate increased with the concentration. However, as indicated by the Monod kinetic model, the organic removal rate would first increase hyperbolically with concentration and then exhibit an asymptotic behavior with higher concentrations. Therefore, the organic removal rate increased at a lesser degree than the concentration increase at the upper range of organic concentrations. The resultant% BOD_5 removal was thus decreased while the

amount of BOD_5 removed still increased. A 37% decrease in the percentage BOD_5 removal was observed with increases in the initial PGME concentration from 100 to 500 ppm.

3.2.3. Effect of liquid flow rate, initial liquid distribution and bed height

Varied liquid flow rates from 0.184 to 0.918 kg m^{-2} s^{-1} were used to examine the effect of liquid flow rate on the removal of PGME in a trickle bed filter. The initial concentration of PGME was kept at 300 ppm for all runs.

Fig. 7 shows the variation of the percentage BOD_5 removal after 96 h of treatment and the liquid hold-up in the tall bed ($H/D = 4.6$) with liquid flow rate. Increases in the liquid flow rate from 0.184 to 0.918 kg m^{-2} s^{-1} resulted in a marginal increase in the percentage BOD_5 removal from about 80% to 85% for MPD and 71% to 74% for SPD as can be seen in Fig. 7. It is relevant to note that the lower percentage BOD_5 removal with SPD corresponds to the lower liquid hold-up as compared to the case with MPD. In addition, when the liquid flow rate was increased beyond 0.551 kg m^{-2} s^{-1}, no further enhancement in the percentage BOD_5 removal was observed as indicated by the plateau section in Fig. 7. This might be due to liquid channeling in the centre region of the column at higher flow rates; hence, liquid-biomass contact in the packed bed was not improved further with liquid flow rate significantly, resulting in the leveling off of the BOD_5 removal in this range of liquid flow rates. The increasing trend of the percentage BOD_5 removal in the present study appears to be in contrast with other authors' results published in the literature. Generally, in a continuous process the percentage organic removal decreased with increases in the liquid flow rate because the liquid residence time inside the bed decreased with liquid flow rate [26]. In present study, the trickle bed was operated under a batch-recirculation mode with continuous recycle of liquid. Although the liquid residence time per pass decreased with increases in liquid flow rate, the number of passes increased. Thus, for all runs regardless of the liquid flow rate, the overall liquid residence time inside the trickle bed in fact remained the same over the duration of the experiment.

A slight increase in the percentage BOD_5 removal with liquid flow rate could be attributed to better wetting of the biofilm on the

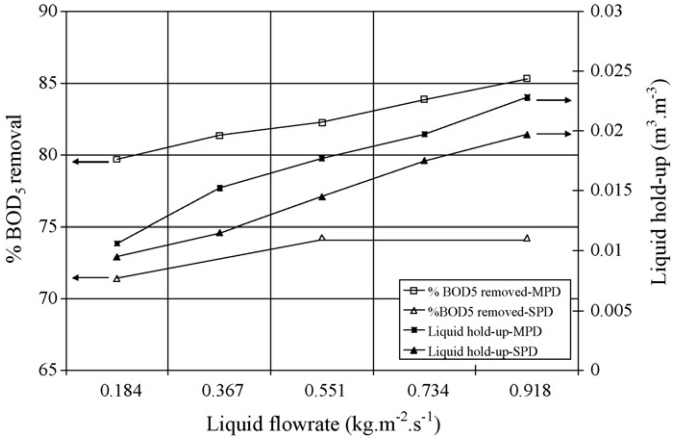

Fig. 7. BOD_5 removal and liquid hold-up at various liquid flowrates with $H/D = 4.6$.

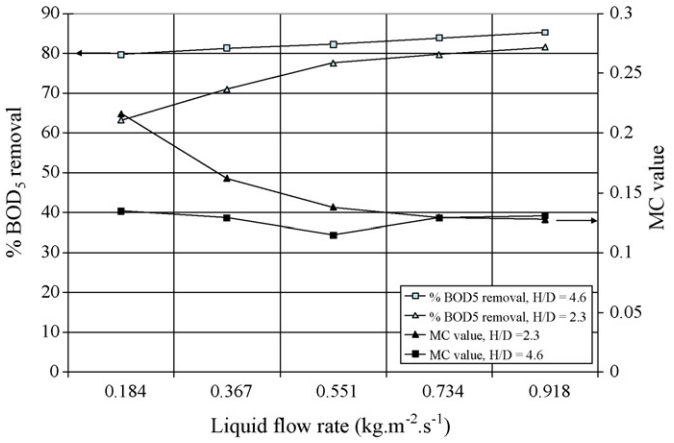

Fig. 8. BOD_5 removal and liquid distribution factor vs. flowrate and bed height using MPD.

packing surface at higher liquid flow rates, resulting in a higher active area on the biofilm for the organic biodegradation. The overall microbial activity was reported to be proportional to the wetting of the packing since more biofilm grew on the wet packing [27,28]. Liquid hold-up in the bed increased at higher liquid flowrates. This in turn enhanced the wetting of the packing [17]; and hence, the wastewater-biofilm contact was improved. Therefore, the percentage BOD_5 removal increased with the dynamic liquid hold-up as shown in Fig. 7.

The variation of the percentage BOD_5 removal and the liquid distribution coefficient MC with liquid flow rate, using MPD with two bed heights, is shown in Fig. 8 . For the short bed of $H/D = 2.3$, the MC value decreased significantly with increases in the liquid flow rate from 0.184 to 0.918 kg m^{-2} s^{-1} while the percentage BOD_5 removal increased about 29%. The variation of the percentage BOD_5 removal with the liquid flow rate follows an increasing trend for both bed heights. However, the percentage BOD_5 removal for the tall bed was greater than that of the short bed, especially at low liquid flow rates. The improvement of the BOD_5 removal with the tall bed was due to an increase in the liquid retention time in the bed when the bed height was increased. Similar observation was also reported in literature [29,30].

Liquid distribution was also improved with bed height as reflected by the lower MC values for the tall bed; hence, liquid-biofilm contact was enhanced, resulting in better organic removal. Fig. 8 also shows that the percentage BOD_5 removal by the short bed approached that of the tall bed (within 5%) at liquid flow rates $\geq$0.551 kg m^{-2} s^{-1}. At higher liquid flow rates, liquid distribution in the shallow bed was improved significantly and the corresponding MC approached the asymptotic trend of the MC value for the tall bed.

3.2.4. Effect of local liquid distribution on local BOD_5 removal

In order to determine the effect of liquid distribution on the local BOD_5 removal, a series of experiments were conducted under a continuous mode. A set of liquid collecting cells in a diagonal pathway across the liquid collector was selected, and

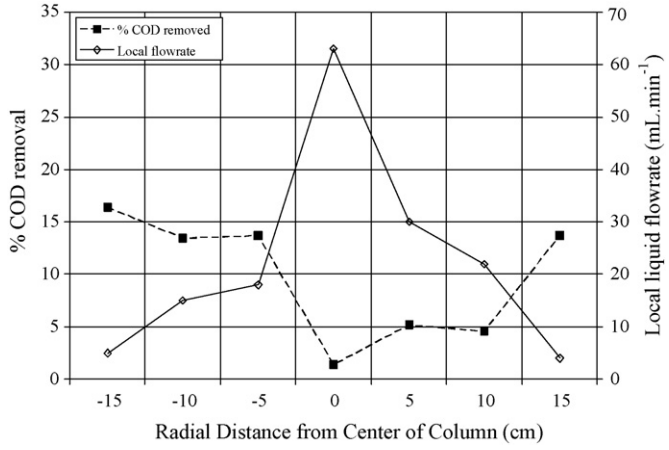

Fig. 9. Radial profiles of COD removal and local liquid flowrate using MPD at $H/D = 4.6$, a total liquid rate of 0.367 kg m^{-2} s^{-1} and an initial organic concentration of 300 ppm.

the liquid flow rates to these cells were measured. The water samples from these cells were also analyzed for the BOD_5 and COD contents. The initial PGME concentration was kept at 300 ppm for all runs.

The typical results obtained at the liquid flow rate of 0.367 kg m^{-2} s^{-1} are presented in Figs. 9 and 10 . In these figures, the local percentage BOD_5 and COD removal and the local liquid flow rate are plotted against the radial position with the zero position being at the centre of the bed. It can be seen that, similar to liquid distribution, the BOD_5 and COD removal was not uniform over the bed cross section. The regions with higher liquid flow rates correspond to lower BOD_5 and COD removal and vice versa. At a given bed height, local liquid retention time was lower with a higher local liquid flow rate. On the other hand, the biodegradation was a slow process requiring a sufficient retention time of water in the bed. Accordingly, a lower retention time resulted in a lower organic removal as reflected by a lower BOD_5 removal.

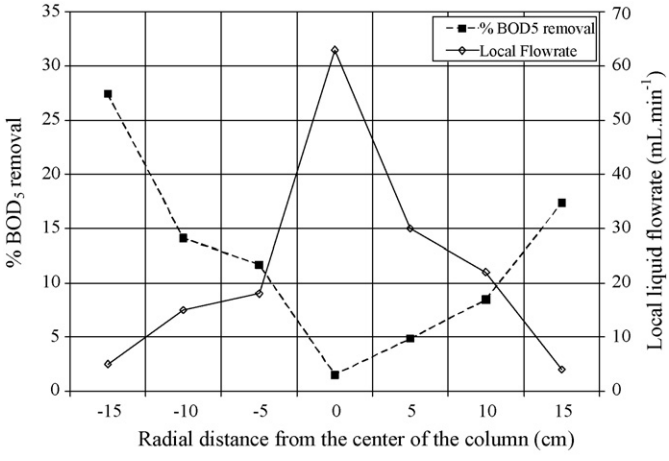

Fig. 10. Radial profiles of BOD_5 removal and local liquid flowrate using MPD at $H/D = 4.6$, a total liquid rate of 0.367 kg m^{-2} s^{-1} and an initial organic concentration of 300 ppm.

4. Conclusion

Liquid distribution and dynamic liquid hold-up in a trickle bed were measured and their effect on the BOD_5 removal was investigated. Liquid distribution and dynamic liquid hold-up were found to increase with liquid flowrate, as expected. Liquid distribution was more uniform with the MPD and the tall bed ($H/D = 4.6$). Also, the dynamic liquid hold-up was higher with MPD than SPD. Moreover, in the presence of the biofilm on the packing surface, the dynamic liquid hold-up increased about 20%, on the average, compared to that of a clean bed.

For both MPD and SPD with $H/D = 4.6$, the effect of liquid flow rate over the range from 0.184 to 0.918 kg m^{-2} s^{-1} on the percentage BOD_5 removal was marginal. On the other hand, the bed height affected the BOD_5 removal substantially, especially at a low flow rate of 0.184 kg m^{-2} s^{-1}, at which a 25% increase in the percentage BOD_5 removal was observed when the bed height was increased from 0.7 m ($H/D = 2.3$) to 1.4 m ($H/D = 4.6$). However, due to significant improvement of liquid distribution in the short bed ($H/D = 2.3$) at liquid flow rates $\geq$0.551 kg m^{-2} s^{-1}, only 5% increase in the percentage BOD_5 removal with bed height was observed.

Local liquid flow and local BOD_5 removal were also measured. Radial distribution of local BOD_5 removal was found to be non-uniform and it was affected by local liquid flow distribution across the bed cross-section. Local BOD_5 removal decreased with increases in the local liquid flowrate due to decreases in local liquid retention time.

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