

Oxygen mass transfer and hydrodynamics in a multi-phase airlift bioscrubber system

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ABSTRACT

The addition of select polymer beads to stirred tank bioscrubber systems has been shown to greatly enhance the removal and treatment of toxic VOCs via the capture and sequestration of poorly soluble compounds such as benzene, and the release of these materials, based on equilibrium partitioning, to microorganisms in the aqueous phase. In this study, oxygen volumetric mass transfer coefficients were determined for an 11 L airlift vessel containing tap water alone, tap water with Nylon 6,6 polymer beads (10% v/v), and tap water with silicone rubber beads (10% v/v), over various inlet gas flow rates, with the aim of initially characterizing a low-energy pneumatically agitated reactor (concentric tube airlift). In addition, oxygen transfer rates into the airlift with and without polymers with high oxygen affinity were determined. To further characterize this reactor system, a residence time distribution analysis was completed to determine hydrodynamic parameters including the Peclet number (Pe), circulation time (t_c) and mixing time (t_m) over various gas flow rates for the airlift containing tap water with and without silicone rubber. It was found that the addition of silicone rubber beads, which has a high affinity for oxygen, reduced the measured volumetric mass transfer coefficient relative to a system without polymers due to oxygen sorption during the dynamic period of testing, but increased the overall amount of oxygen that was transferred to the system during the dynamic period. The addition of Nylon 6,6, which has very low oxygen uptake, allowed for estimation of the physical effect of solids addition on gas–liquid mass transfer and it was found that there was no effect on the measured volumetric mass transfer coefficient relative to a system without polymers. However, hydrodynamic parameters revealed that the addition of silicone rubber into an airlift vessel improves liquid phase mixing. This investigation has defined key operational features of a low-energy three-phase airlift bioscrubber system for the treatment of toxic VOC substrates.

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1. Introduction

Airlift vessels are a useful reactor design due to their simple construction, low-energy requirements and low shear environment (Chisti, 1989). Recently, Littlejohns and Daugulis (2009) examined the performance of a novel airlift solid–liquid two-phase partitioning bioreactor (TPPB) for the treatment of a gaseous mixture of benzene, toluene, ethylbenzene and *o*-xylene (BTEX). The addition of a solid phase, composed of silicone rubber beads, to an airlift bioreactor was shown to increase performance during fluctuating inlet BTEX loadings relative to an airlift without silicone rubber. This was due to silicone rubber absorbing/desorbing BTEX according to achieving equilibrium conditions while meeting metabolic demand, which increased substrate gas–liquid mass transfer and maintained BTEX aqueous phase concentrations at sub-inhibitory levels. However, during this investigation it was found that oxygen

mass transfer from the gas to the aqueous phase was the rate limiting step for biodegradation, as dissolved oxygen (DO) reached 0% at average elimination capacities of $31.2 \text{ g m}^{-3} \text{ h}^{-1}$ and removal efficiencies of 49.8% during steady-state loadings of $60 \text{ g m}^{-3} \text{ h}^{-1}$. In addition, overall system performance of the airlift TPPB was lower in comparison to a stirred tank TPPB treating a BTEX contaminated gas stream whose DO remained over 80% while achieving elimination capacities of $58.5 \text{ g m}^{-3} \text{ h}^{-1}$ and removal efficiencies of 97.1% at a steady-state loading of $60 \text{ g m}^{-3} \text{ h}^{-1}$ (Littlejohns and Daugulis, 2008).

Characterization of oxygen mass transfer within the airlift TPPB is of interest, as past research has determined that the presence of an immiscible sequestering phase in a mechanically agitated TPPB enhances the oxygen transfer rate (OTR) to the system relative to single phase systems. This has been shown to be the case for a TPPB using the organic solvent, *n*-hexadecane, which has a high affinity for oxygen, as oxygen transfers in parallel from the gas phase to the aqueous/solvent phases which have a higher combined DO saturation concentration (Nielsen et al., 2005). The presence of silicone rubber beads, which also have a high affinity for oxygen, have also provided an increase in OTR in a stirred tank TPPB due to mass transfer in

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series from the gas phase to the aqueous phase, then subsequently from the aqueous phase to the polymer phase (Littlejohns and Daugulis, 2007). In such arrangements, uptake by the polymer increases the gas–aqueous driving force over dynamic periods. This transport in series model is commonly used for gas–aqueous–solid systems in which the suspended solids are larger than the liquid film thickness between the gas and liquid phases (Alper et al., 1980). In addition, it was also demonstrated by Littlejohns and Daugulis (2007) that the addition of polymers in a stirred tank has a physical enhancement effect on oxygen mass transfer. Physical enhancement of gas–liquid mass transfer in three-phase systems has been observed in several studies (Zhang et al., 2006; Ruthiya et al., 2003; Tinge and Drinkenburg, 1995) and is caused by enhanced boundary layer mixing due to turbulence at the gas–liquid interface (Zhang et al., 2006; Ruthiya et al., 2003), resulting in a larger refreshment rate of liquid in the boundary layer by mixing with the bulk fluid. In addition, physical enhancement may involve changes in the gas–liquid interfacial area by coalescence inhibition caused by particles being present at the gas–liquid interface (Ruthiya et al., 2003).

In addition to oxygen mass transfer, hydrodynamic characterization of airlift bioreactors provides important information necessary to describe system performance and facilitate mathematical modeling. In contrast to stirred tank vessels that are assumed to be well-mixed, airlift bioreactors can often have an axial variation of composition, particularly in the downcomer (Chisti, 1989). Hydrodynamic studies have shown that the presence of solids in three-phase systems can have a neutral (Sánchez et al., 2005; Lindert et al., 1992) and positive (Comte et al., 1997; Lu et al., 1995) impact on mixing depending on the reactor geometry, solid size, solid density and solid loading.

Despite the numerous studies on oxygen mass transfer and mixing in three-phase airlift bioreactors, the airlift partitioning bioreactor has not been characterized to date due to the unique physical properties of the solid phase. The purpose of this study was to determine the impact of silicone rubber beads in an airlift reactor on the measured effective volumetric mass transfer coefficient ($k_L a_{eff}$) over a range of air flow rates relative to the $k_L a_{eff}$ in an airlift containing solids with low oxygen affinity (Nylon 6,6) and to the volumetric mass transfer coefficient in airlift without solids ($k_L a$). Results were compared to the volumetric mass transfer coefficient of a stirred tank containing silicone rubber, Nylon 6,6 and without solids. The OTR was then determined in the airlift with and without silicone beads to show the true amount of oxygen entering each system. In addition, hydrodynamic characterization was completed for an airlift with and without silicone rubber beads by quantifying Peclet number (Pe), circulation time (t_c) and mixing time (t_m). This work has provided insight into the observed performance of an airlift TPPB for treatment of BTEX contaminated gases in previous work (Littlejohns and Daugulis, 2009). In addition this work has determined the impact of the addition solids with high oxygen affinity on mass transfer and hydrodynamics in an airlift, which had not been undertaken to date.

2. Materials and methods

2.1. Equipment

The reactor used was a 13 L Chemap AG Series 3000 concentric tube airlift fermentor (Männedorf, Switzerland) with dimensions listed in Table 1. All experiments were conducted at $30 \pm 0.1^\circ\text{C}$ and DO and pH were monitored continuously by probes located at the bottom of the vessel using a Measurement Computing TracerDAQ data acquisition system. Throughout all experimentation, the working volume of the reactor was 11 L with either no solid phase or with 10% v/v polymer beads. The polymer used with a

high affinity for oxygen (O_2 diffusivity = $3.4 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ (Merkel et al., 2000), O_2 solubility = $0.18 \text{ cm}^3(\text{STP}) \text{ cm}^{-3} \text{ atm}$ (Merkel et al., 2000)) was silicone rubber that was obtained from GE-Mastercraft® in the form of 100% silicone rubber caulking dried to spherically shaped beads (diameter = 2.5 mm). The polymer used with a low affinity for oxygen (O_2 diffusivity = $1.6 \times 10^{-9} \text{ cm}^2 \text{ s}^{-1}$ (Jarus et al., 2002), O_2 solubility = $0.035 \text{ cm}^3(\text{STP}) \text{ cm}^{-3} \text{ atm}$ (Weinkauff et al., 1992)) was Nylon 6,6, which was obtained from Dupont Canada (diameter = 2.59 mm). The stirred tank used was described previously (Littlejohns and Daugulis, 2007).

2.2. Oxygen volumetric mass transfer coefficients

$k_L a$ for the airlift reactor containing solely tap water was determined for flow rates of 0.03, 0.18, 0.27, 0.36, 0.45 and 0.54 vvm while $k_L a_{eff}$ for the airlift containing tap water and 10% v/v silicone rubber beads was determined for flow rates of 0.03, 0.18, 0.27 and 0.361 vvm and $k_L a_{eff}$ for the airlift containing tap water and 10% v/v Nylon 6,6 beads was determined for flow rates of 0.27, 0.36, 0.45 and 0.54 vvm. The reason for $k_L a_{eff}$ to be not determined over all flow rates is due to the difficulty of fluidizing Nylon 6,6 at low flow rates arising from its slightly higher density than water. Silicone rubber was studied at higher flow rates due to its hydrophobicity and tendency to stay at the gas–liquid interface. The $k_L a_{eff}$ and $k_L a$ for the stirred tank system were determined at 800 rpm at 0.17, 0.25 and 0.33 vvm in all cases (Littlejohns and Daugulis, 2007).

To determine $k_L a$ and $k_L a_{eff}$, the unsteady-state method was used as described by Shuler and Kargi (2002). The vessel was first sparged with nitrogen gas in order to remove all oxygen from the system then air was delivered from a three-hole sparger located at the bottom of the riser column. For consistency, data between 10% and 80% of DO saturation were used for the determination of $k_L a$ and $k_L a_{eff}$, according to Eq. (1)

$$\text{OTR} = \frac{dC_L}{dt} = k_L a(C_L^* - C_L) \quad \text{or} \quad \frac{dC_L}{dt} = k_L a_{eff}(C_L^* - C_L) \quad (1)$$

where C_L is the DO concentration in the liquid phase (mg L^{-1}) and C_L^* is the saturation concentration of oxygen in the liquid phase (mg L^{-1}). Surface aeration effects were found to be negligible by determining that $k_L a$ and $k_L a_{eff}$ were much larger when using sparging than without (data not shown). Probe response times were also found to have a negligible effect on $k_L a$ and $k_L a_{eff}$ over the flow rates used in this study, using an earlier method (Littlejohns and Daugulis, 2007) wherein the probe response time constant was found to be 13.5 s.

Since airlift bioreactors have a concentration profile that is axially distributed, it must be determined if Eq. (1), which assumes the vessel to be well-mixed, is accurate to describe $k_L a$ and $k_L a_{eff}$ throughout an airlift vessel. Andre et al. (1983) determined $k_L a$ using a tanks-in-series model to account for axial distribution and compared it to the $k_L a$ obtained using Eq. (1) with a single probe located at the bottom of the airlift vessel. It was found that if Eq. (2) holds true, then Eq. (1) provides an accurate estimate of the $k_L a$ determined using the tanks-in-series model,

$$k_L a \times t_c \leq 2 \quad \text{or} \quad k_L a_{eff} \times t_c \leq 2 \quad (2)$$

where t_c is the circulation time in the airlift (s). Determination of this hydrodynamic parameter will be described in the following section. It was found that the data obtained in this study satisfied Eq. (2), and therefore it is valid to use Eq. (1) to determine $k_L a$ and $k_L a_{eff}$ in the airlift reactor. This assumption is consistent with other authors who have used a well-mixed model (Eq. (1)) to determine $k_L a$ in airlift vessels larger than the one in the current study (Lindert et al., 1992; Freitas and Teixeira, 2001; Guo et al., 1997).

OTR for the airlift with a single aqueous phase only was determined using Eq. (1). For the airlift containing silicone rubber, OTR

Table 1
Geometry of airlift bioreactor.

D_T (m), tank diameter	D_R (m), riser diameter	h_T (m), tank height	h_R (m), riser height	A_d/A_r , downcomer cross-sectional area/riser cross-sectional area	V_r (L), riser volume	V_d (L), downcomer volume	V_T (L), total volume
0.14	0.1	0.76	0.53	1.96	4.16	4.43	11

was determined based on the approach described in Littlejohns and Daugulis (2007), which results in Eq. (3),

$$\text{OTR} = k_L a \left(\frac{V_L}{V_P + V_L} \right) (C_L^* - C_L) \quad (3)$$

where V_L is the liquid volume (L) and V_P is the polymer volume (L). For consistency in OTR determination for all runs, data between 10% and 80% of DO saturation was used. The amount of oxygen transferred to the system with and without polymers was then determined by fitting a polynomial to the OTR curve using MATLAB[®], then integrating the polynomial and multiplying the result by the working volume of the reactor.

2.3. Residence time distribution

The residence time distribution (RTD) was investigated in an airlift containing tap water alone and an airlift containing tap water with 10% v/v silicone rubber beads over inlet air flow rates of 0.09, 0.18, 0.27 and 0.36 vvm. Due to this system not being continuous inlet and outlet flow, the present analysis should more appropriately be called a circulation time distribution; however, the term RTD will be used for the remainder of the manuscript due to wide-spread use of this term. RTD experiments were undertaken using tracer experiments consisting of a 5 mL pulse injection of 99.7% pure acetic acid from Fisher Scientific (Nepean, Canada) 10 cm from the top surface of the working volume and subsequent measurement of the tracer until uniformity within the reactor was reached. Acetic acid was selected as the tracer based on tracer criteria outlined by Swaine and Daugulis (1988). Eq. (4) can be used to describe the RTD for a pulse injection when injection and detection are at different points in a loop reactor (Takao et al., 1982) and can be fit to the experimental tracer response curve by estimating the Peclet number, Pe ,

$$\frac{C_t}{C_{t,\infty}} = \frac{1}{2} \sqrt{\frac{Pe}{\pi\theta}} \sum_{j=-\infty}^{\infty} \exp\left(-\frac{Pe(j+z^*-\theta)^2}{4\theta}\right) \quad (4)$$

where

$$Pe = \frac{U_c L}{D_{ax}} \quad (5)$$

C_t is the dynamic measurement of pH, $C_{t,\infty}$ is the final pH at equilibrium, θ is the dimensionless time (t/t_c), z^* is the dimensionless geometrical distance between injection and detection (z/L), U_c is the mean circulation velocity (m s^{-1}), L is the mean reactor length (m), and D_{ax} is the axial dispersion coefficient ($\text{m}^2 \text{s}^{-1}$). The experimental data were fit to this model by minimizing the sum of squares error, which provided an estimate of Pe . RTD experimentation also allowed for the estimation of circulation time (t_c) and mixing time (t_m). The circulation time can be estimated by the graphical measurement of the time it takes between two consecutive peaks on the RTD response curve. The mixing time was determined by measuring the time it took the RTD response curve to reach equilibrium. For this study, considering pure error in pH measurement, equilibrium was reached when the normalized tracer curve reached 1 ± 0.05 . It should be noted that this approach assumes equal liquid velocities in the riser and downcomer, which is valid as the areas of the riser and

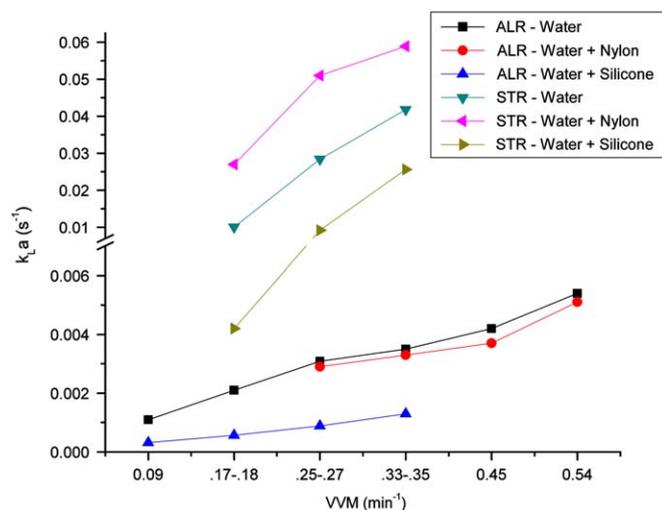


Fig. 1. $k_L a$ and $k_L a_{eff}$ for airlift systems for a range of inlet gas flow rates.

downcomer are approximately equal. This approach also assumes identical dispersion coefficients in each section which may not be exact as it is known that the downcomer is considerably more plug flow than the riser (Chisti, 1989). However, this approach is deemed valid for the purposes of comparison between systems.

3. Results and discussion

3.1. Oxygen volumetric mass transfer coefficients

Fig. 1 shows $k_L a$ for the single phase system and $k_L a_{eff}$ for the systems containing Nylon 6,6 and silicone rubber, for both the airlift and the stirred tank vessels. For all cases, $k_L a$ and $k_L a_{eff}$ increased with gas flow rate, which is a trend that has been observed for reactors with and without solids by several other authors (Giovannetone and Gulliver, 2008; Guo et al., 1997; Hwang and Lu, 1997). For both the stirred tank and airlift, relative to the single phase systems, the vessels containing silicone rubber beads had a reduced $k_L a_{eff}$ over all measured flow rates. Reduced mass transfer coefficient in stirred tank systems with second phases possessing high oxygen affinities has been observed by several authors for reactors containing liquid phases of *n*-hexadecane (Nielsen et al., 2005), alkanes *n*-C₁₂₋₁₃ (at < 800 rpm) (Clarke et al., 2006), polymer phases of silicone rubber (Littlejohns and Daugulis, 2007) and extensospere particles of 55–60% SiO₂ (Sánchez et al., 2005). The observed decrease in $k_L a_{eff}$ can be attributed to the uptake of oxygen by the silicone rubber during the dynamic period of $k_L a_{eff}$ measurement. As the oxygen is absorbed by the polymer, the DO within the aqueous phase is reduced, causing the aqueous phase to take longer to reach saturation. In an aqueous-polymer or immiscible aqueous-liquid mixture, a polarographic DO probe measures the partial pressure of oxygen within the aqueous phase, which is the partial pressure of oxygen within the system. As both the aqueous and sorbent phase will have equal partial pressures at equilibrium concentrations that are not equal, the DO measurements, and therefore the $k_L a_{eff}$ measurements, will

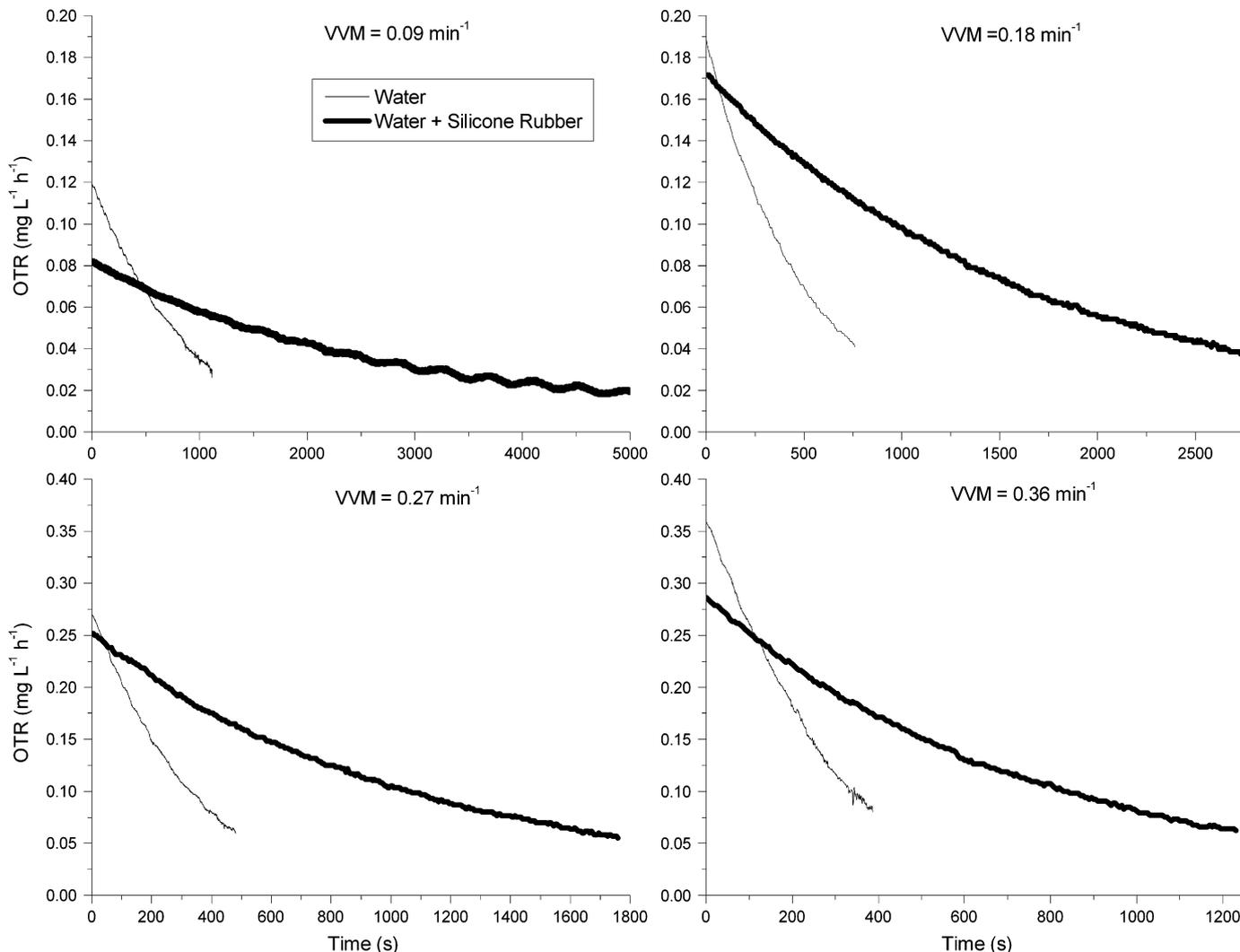


Fig. 2. OTR for airlift reactors with and without silicone rubber from 10% to 80% DO saturation.

correspond only to aqueous phase concentration and will not account for the increased concentration in the working volume due to the presence of the sorbent. Therefore, a lower $k_L a_{eff}$ does not necessarily indicate that the gas–aqueous mass transfer is reduced by the presence of polymers, as the measured DO is the outcome of transfer from aqueous phase to the polymers subtracted from transfer from the gas to aqueous phase.

Fig. 1 also shows that in the airlift Nylon 6,6 did not have a significant effect on $k_L a_{eff}$ relative to the airlift without solids, whereas the addition of Nylon 6,6 into a stirred tank caused an increase of up to 45% relative to the single phase stirred tank system. This is an interesting result, as Nylon 6,6 was previously used as an inert control in a mechanically agitated TPPB to demonstrate that the addition of polymers into the bioreactor can result in the physical enhancement of gas–liquid mass transfer by increasing $k_L a_{eff}$ (Littlejohns and Daugulis, 2007). However, the results of the current study are in agreement with Lindert et al. (1992) who determined that the addition of polycarbonate beads of density 1241 kg m^{-3} and diameter 2.7 mm, which have a low affinity for oxygen, to an external loop airlift bioreactor had no significant impact on $k_L a_{eff}$ relative to a bioreactor without polymers. It is speculated that this can be attributed to

the high shear environment of the stirred tank relative to the airlift, resulting in physical enhancement due to the Nylon 6,6. One mechanism that has been proposed for the physical enhancement of $k_L a$ in bioreactors involves increased turbulence at the gas–liquid interface (Zhang et al., 2006; Ruthiya et al., 2003), and turbulence in the airlift is reduced in comparison to the stirred tank at 800 rpm. The magnitude of $k_L a_{eff}$ and $k_L a$ are larger for the stirred tank compared to the airlift by 16.4, 13.4 and 20.1 times for the systems with Nylon 6,6, silicone rubber and the single phase systems, respectively, at a gas flow rate of 0.33–0.35 vvm (in order to be able to compare all systems). The results from Fig. 1 help to explain the increased performance of the stirred tank TPPB (Littlejohns and Daugulis, 2008) compared to the airlift TPPB (Littlejohns and Daugulis, 2009) for the treatment of BTEX contaminated gases, as the results of the present study indicate that the polymers within the airlift TPPB did not physically enhance gas–liquid mass transfer as they did in the stirred tank and stirred tank gas–liquid mass transfer is more rapid.

The OTR, which provides a more complete measure of mass transfer from the gas phase to the reactor system by taking into account both $k_L a$ and gas–liquid driving force, is shown in Fig. 2 for the single phase airlift case and the airlift with silicone rubber beads between

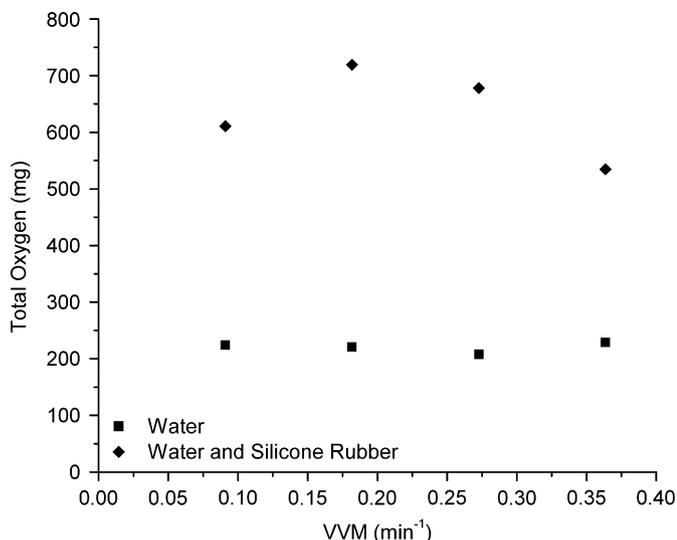


Fig. 3. Total oxygen transferred to the airlift reactor with and without silicone rubber beads over 10–80% DO saturation.

10% and 80% DO saturation. It can be seen that the system without polymers has a larger initial instantaneous OTR compared to the system with silicone rubber (up to 31% at $t = 0$), however, it takes the airlift containing silicone rubber up to 4.5 times as long to reach 80% of DO saturation compared to the single phase case. This shows that, although silicone rubber does not enhance the instantaneous OTR in the airlift, oxygen is being transferred to the system for a longer period of time due to the high affinity of the silicone rubber for oxygen. The amount of oxygen transferred to the airlift reactors between 10% and 80% of DO saturation can be seen plotted in Fig. 3, which shows that the airlift system with polymers contains up to 226% more oxygen by the time that 80% DO saturation is reached in the aqueous phase. This increased oxygen capacity in the airlift containing silicone rubber beads has a benefit for biotic systems, wherein oxygen can be released to the cells in the aqueous phase during dynamic fluctuations that could otherwise lead to oxygen limitations in the system. In addition, this further validates the fact that silicone rubber takes up oxygen from the aqueous phase which reduces $k_L a_{eff}$, as seen in Fig. 1. It should be noted that the impact of particles on physical enhancement of gas–liquid mass transfer can be affected by particle hydrophobicity (Schumpe et al., 1987); however, in the calculations used for OTR in the current study, it has been assumed that silicone rubber has no physical enhancement effect on gas–liquid mass transfer in a similar manner to Nylon 6,6.

3.2. Hydrodynamics

Fig. 4 shows Eq. (4) fit to RTD experimental data for a flow rate of 0.09 vvm for an airlift containing a single phase of tap water and an airlift containing tap water with 10% v/v silicone rubber beads, respectively. These predictions, as well as those for all other gas flow rates tested (data not shown), fit well to the RTD experimental data, validating the use of this model to estimate airlift hydrodynamic parameters. In order to fit the experimental data to Eq. (4), Pe was estimated for an airlift with and without silicone rubber beads over a range of gas flow rates, and these estimated values are shown in Fig. 5. Pe is the dimensionless number, defined in Eq. (5), that relates the extent of bulk fluid flow to the extent of dispersion within the airlift vessel. For larger Pe , the airlift system becomes closer to plug flow conditions and when Pe is smaller it indicates that the system is closer to being well-mixed. Within concentric tube airlift

bioreactors, it is often assumed that the downcomer section is plug flow (Kanai et al., 2000; Znad et al., 2004), with the riser column being more well-mixed in nature. It should be noted that this study provides an overall Pe for the airlift vessel, which is commonly reported in studies comparing hydrodynamic parameters in systems under different conditions (Giovannettone and Gulliver, 2008; Merchuk et al., 1998). In Fig. 5, the Pe values trend upwards at higher flow rates and are larger by 60% and 12%, for the system with and without silicone rubber, respectively, over the range of aeration rates employed. This trend is consistent with the literature, as it has been shown that the liquid velocity (Merchuk and Stein, 1981) as well as the axial dispersion coefficient (Giovannettone and Gulliver, 2008) will increase with increasing gas flow rate. Although these will have counteracting effects on Pe , in general, Pe increases with gas flow rate (Chisti, 1989; Sikula and Markoš, 2008). An important observation arising from Fig. 5 is that Pe is larger in an airlift without silicone rubber beads than in a system with solids by up to 41%. This indicates that the addition of the polymer beads improves mixing in the airlift, as a lower Pe indicates that the system is closer to being well-mixed.

The RTD trace was also used to examine the impact of the addition of silicone rubber on reactor hydrodynamics over various gas flow rates, including on circulation time and mixing time. The circulation time is shown for the airlift system with and without silicone rubber beads in Fig. 6. It can be seen that with increased gas flow rate, there is a decrease in circulation time due to the inlet gas inducing a faster liquid velocity for both systems. The airlift containing polymers has slightly higher circulation times (slower liquid velocities) in comparison to the single phase vessel at flow rates of 0.09 and 0.18 vvm by 11.6% and 12%, respectively, but circulation times are similar for both systems at the higher flow rates of 0.27 and 0.36 vvm. The results at lower flow rates are consistent with Guo et al. (1997) who determined that the addition of solids decreased the liquid circulation velocity for external loop airlift bioreactors containing glass beads, polystyrene and Lexan, and Lu et al. (1995), who found the addition of calcium alginate beads reduced liquid circulation velocity in an airlift. This was explained by the solids increasing the drag in the system, particularly for heavier solids. At flow rates of 0.27 and 0.36 vvm the addition of polymers gives no observable effect on circulation time (and therefore liquid velocity), which provides an interesting observation when considered with the finding for Pe for the airlift with and without solids. From Eq. (4), at higher flow rates when liquid velocities of both systems are similar, it appears that the addition of polymers must increase axial dispersion in order to lower Pe relative to the system without polymers.

Mixing time is another hydrodynamic parameter that can be determined from RTD experimentation. Fig. 7 displays mixing times over a range of flow rates for an airlift with and without silicone rubber beads. These data show that t_m decreases with increased gas flow rate, which is an observation that has been reported by other authors (Ganzeveld et al., 1995; Freitas and Teixeira, 1998) and is due to increased gas flow rates causing increased turbulence within the reactor. Fig. 7 also shows that the addition of silicone rubber reduces t_m by up to 33%, and therefore improves mixing efficiency, compared to an airlift without silicone rubber beads. In contrast to the current study, several studies that have observed a decrease in mixing with the addition of solids relative to a system without solids (Sharp et al., 1998; Freitas and Teixeira, 1998), which may be attributed to the difference in solid properties between studies. The oxygen mass transfer and hydrodynamic parameters determined in this study show that the addition of silicone rubber into an airlift vessel does increase mixing of the bulk aqueous phase, but does not provide physical enhancement (interactions with boundary layers or bubble size) of gas–liquid mass transfer. This provides an explanation for previous work that noted reduced performance and oxygen

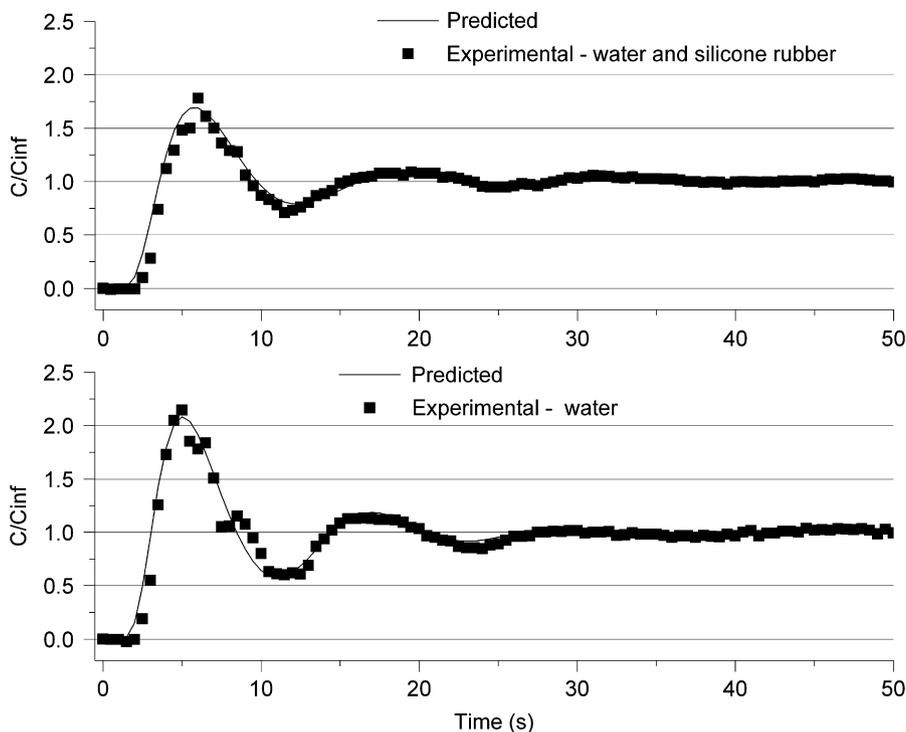


Fig. 4. Predicted (lines) and experimental (squares) tracer response for an airlift containing tap water and silicone rubber (top) and for an airlift containing tap water (bottom).

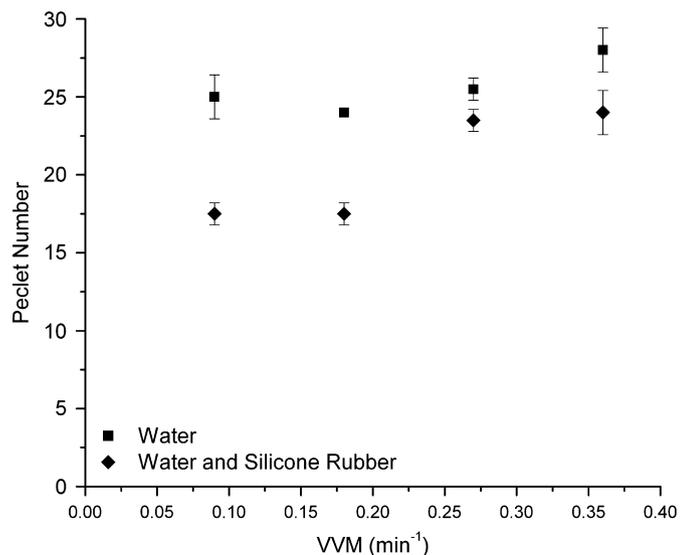


Fig. 5. Peclet numbers for various inlet gas flow rates in an airlift without silicone rubber (squares) and an airlift containing silicone rubber (diamonds).

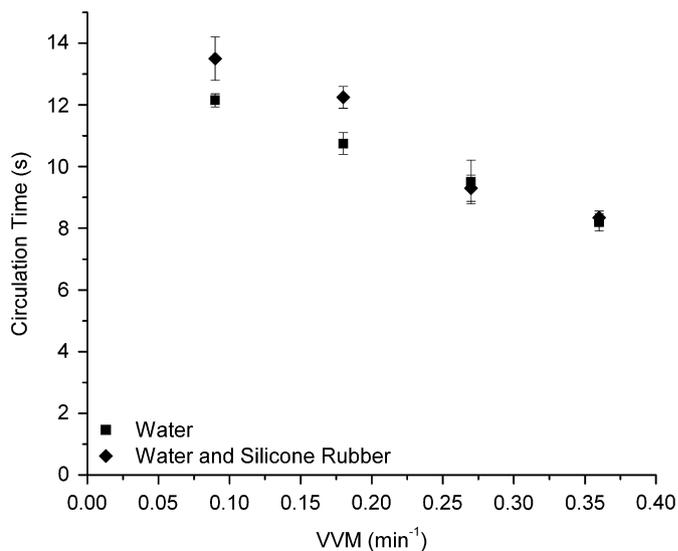


Fig. 6. Circulation time over various inlet gas flow rates in an airlift without silicone rubber (squares) and an airlift containing silicone rubber (diamonds).

limitations in the airlift TPPB (Littlejohns and Daugulis, 2009) relative to the stirred tank TPPB (Littlejohns and Daugulis, 2008) for the treatment of a BTEX contaminated gas stream. However, the addition of polymers can help to relieve oxygen limitations in such bioreactors, as oxygen has been shown to be taken up by the silicone rubber during dynamic periods, which can be released back to the aqueous phase. It should be noted that the effectiveness of these polymers to overcome oxygen limitations depends on the timescale of system dynamics, such as microbial demand and feed fluctuations. The mass transfer and hydrodynamic phenomena associated with the airlift TPPB characterized in this study, are currently being used to

estimate parameters for modeling the airlift TPPB for the treatment of BTEX contaminated gas streams.

4. Conclusions

It was determined in this study that the addition of silicone rubber beads to an airlift vessel reduced the $k_L a_{eff}$ relative to a system without polymers due to the uptake of oxygen by the polymers possessing high oxygen affinity during the dynamic period of measurement. Using Nylon 6,6 as an inert control, it was determined that the addition of polymers likely has no physical enhancement

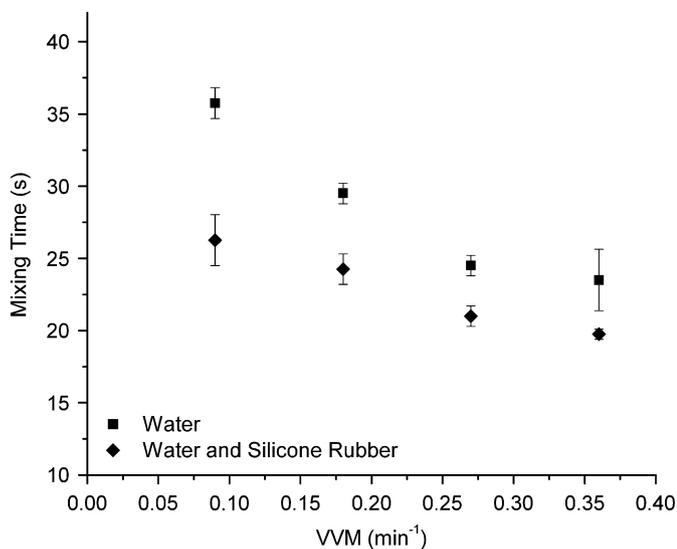


Fig. 7. Mixing time over various inlet gas flow rates in an airlift without silicone rubber (squares) and an airlift containing silicone rubber (diamonds).

on the gas–liquid mass transfer coefficient. OTRs for the airlift with and without silicone rubber showed that, although the airlift without polymers had a larger initial OTR, the system containing silicone rubber had an overall larger mass of oxygen transferred to its working volume. This suggests polymers with a high affinity for oxygen within an airlift bioreactor will deliver oxygen to the aqueous phase during dynamic substrate loadings based on microbial demand. Hydrodynamic parameters from RTD experiments showed that the addition of silicone rubber beads into an airlift vessel enhanced liquid phase mixing, as the Pe , and t_m were lower relative to a system without polymer beads. In addition, t_c was slightly lower for the system containing silicone rubber beads at lower gas flow rates. The data obtained in this study have provided characterization of a unique three-phase airlift system and useful parameters for use in mathematical models currently under development.

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