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Intensification of gas–liquid mass transfer using a rotating bed of porous packings for application to an *E. coli* batch fermentation process

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Abstract

In the present study, the intensification of oxygen transfer in an *E. coli* fermentation system has been investigated by employing various types of highly porous packing elements as agitators in batch fermentors. Three types of porous materials namely Declon© mesh, compact fibre mesh and knitted stainless steel wire mesh were first characterised in terms of their mass transfer performance and their power consumption in air–water and air/50% water–50% glycerol (v/v) mixture representing Newtonian liquid viscosities of 0.7 and 4.7 mNs/m^2, respectively, at 35 °C. Comparisons between the porous impellers and a conventional double Rushton turbine impeller indicate the transfer of oxygen into the liquid medium is approximately doubled with the knitted wire mesh design for the range of agitator speeds tested at 1 vvm aeration rate. For example, a volumetric mass transfer coefficient, K_La, of 0.048 s^{-1} is achieved at a power input of 1000 W/m^3 using 40 cm length of knitted wire mesh attached to the shaft in air/water system at 1 vvm of aeration rate compared to K_La of 0.021 s^{-1} obtained with the double Rushton turbine at the same power input. The degree of mass transfer enhancement is even greater with the knitted wire mesh in the more viscous liquid system compared to the Rushton turbine at similar power inputs. The potential for achieving the principle of process intensification is demonstrated by the knitted wire mesh where mass transfer performance is improved without increased power consumption through a more efficient rotating packed bed design.

Preliminary tests to evaluate the application of the porous impeller designs in real fermentation systems show that the knitted wire mesh impeller resulted in higher overall *E. coli* cell growth rate than the Rushton turbine. This may be attributed to its higher oxygen transfer capability than the Rushton turbine. More tests are currently underway to study these effects in more detail.

Keywords: Process intensification; Rotating packed bed; Porous packings; Gas–liquid mass transfer; *E. coli* fermentation

1. Introduction

Traditionally, the mechanically agitated vessel using multiple impellers typically of a Rushton turbine or a propeller design configuration has been, and still is, widely employed as fermentation reactor in many large-scale commercial applications [1–4]. Their main advantages are that they are highly flexible and they can achieve relatively high oxygen transfer rates in low to moderate viscosity medium. However, it is recognised that these stirred tank reactors (STR) are far from ideal for specific applications involving, for example, shear-sensitive plant or animal cells [5,6], viscous fermentation broths [7] and high density cell cultures. In high density cell cultures, the uptake rates of oxygen by the micro-organisms can be so high that the rate of oxygen that can be transferred from the air supply to the liquid limits the cell growth rate. This oxygen transfer limitation may be further exacerbated by the highly viscous liquid system which is often a direct consequence of the high cell concentrations [8]. Another limiting constraint on the transfer of oxygen is the naturally poor solubility of O_2 in water at standard temperature and pressure. With the drive for business operations to increase productivity and keep costs low in order to remain competitive in the market, there is scope and a need to intensify the mass transfer operation under these conditions.

Several alternatives have been developed to address some of the problems associated with the use of the conventional STR. The air-lift reactor and the bubble column reactor have been developed and adopted industrially for shear-sensitive, low viscosity systems [9–15]. Attempts at intensification of these designs have been made, for example, by the use of static mixers to improve oxygen transfer [16–18], high density cultures to improve productivity [19] and increased aeration rate for improved solid–liquid mass transfer in slurry processes [9].

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Nomenclature

C	dissolved oxygen concentration in bulk liquid phase (%sat or mol L^{-1})
C^*	dissolved oxygen saturation concentration (mol L^{-1})
C_L	normalised dissolved oxygen concentration
C_p	normalised dissolved oxygen concentration measured by probe
K_La	volumetric mass transfer coefficient (s^{-1})
k_p	probe sensitivity (s)
OTR	oxygen transfer rate (mol L^{-1} h^{-1})
OUR	oxygen uptake rate of micro-organisms (mol L^{-1} h^{-1})
P	power (W)
q_{O_2}	specific respiration rate of micro-organisms (mol L^{-1} g^{-1} h^{-1})
t	time (s)
t_m	mass transfer time (s)
U_s	superficial air velocity(m/s)
V	liquid volume (m^3)
X	total biomass (g)

Greek symbol

τ_p	probe response time (s)
μ	viscosity of medium (mNs/m^2)
μ_w	viscosity of water (mNs/m^2)

Oxygen transfer rate (OTR) to the liquid medium in fermentation reactors depends on several factors as expressed in Eq. (1):

$$\text{Mass transfer rate (OTR)} = K_La(C^* - C) \quad (1)$$

The volumetric mass transfer coefficient 'K_La' may be increased by augmenting the interfacial area 'a' through the formation of smaller gas bubbles which have greater surface area to volume ratio than larger bubbles. In many fermentation reactors, however, subsequent coalescence into larger bubbles presents a pertinent problem, which reduces the mass transfer capability of the system.

High voidage packing material has been used as bubble splitters in earlier work [20] and has been shown to be extremely effective for breaking up large gas bubbles into fine bubbles of the order of 300–500 μm. Their application in coalescing systems has also been demonstrated whereby the formation of smaller bubbles is sustained with little risk of coalescence. Similar oxygen transfer enhancement has been demonstrated with porous nylon packing in the riser section of an air-lift bioreactor which was attributed to decreased bubble size and higher gas hold-up for increased contact time [21]. In contrast, stable bubble diameters using conventional impellers are typically of the order of 1–5 mm [22] and formation of smaller bubbles is an energy intensive process in such systems.

Our ultimate aim in this research programme is to exploit the mass transfer enhancements of the porous packing elements in an intensified continuous flow bioreactor and use them as natural immobilisation supports for micro-organisms. In this way, the packings and immobilised cells can be re-used in an integrated reactor/separator system where expected high cell densities will allow high reactor productivity to be achieved. The present study, which represents the initial stages in the development of the intensified continuous flow bioreactor, explores the potential of using a rotating bed of highly porous packing element in a stirred tank vessel in an attempt to intensify oxygen transfer rates in aerobic fermentations using high cell density cultures. It is expected that the porous packing will fulfil the dual purpose of producing small bubbles and providing agitation through the fermentation medium.

2. Experimental

Initial oxygen transfer experiments were carried out in de-ionised water and a mixture of 50% water/50% glycerol representing liquid viscosities at 35 °C of 0.7 and 4.7 mNs/m^2 [23], respectively. The performance of the various packing materials was investigated in terms of their mass transfer performance measured by K_La and their corresponding power consumption in relation to operating conditions of agitation rates, aeration rates and fluid viscosity. In subsequent experiments, the performance of the knitted wire mesh packing was evaluated against that of the double Rushton turbine impeller in an *E. coli* fermentation system.

2.1. Apparatus and procedure

All experimentation was carried out in a 5 L (4 L working volume) glass stirred tank baffled BioFio III reactor (New Brunswick Scientific) (Fig. 1) of diameter D_T of 18 cm equipped with a 12 mm polarographic dissolved oxygen probe (InPro® 6800, Mettler Toledo, UK) for measuring dissolved oxygen (DO) partial pressure. Built-in feedback controllers for temper-

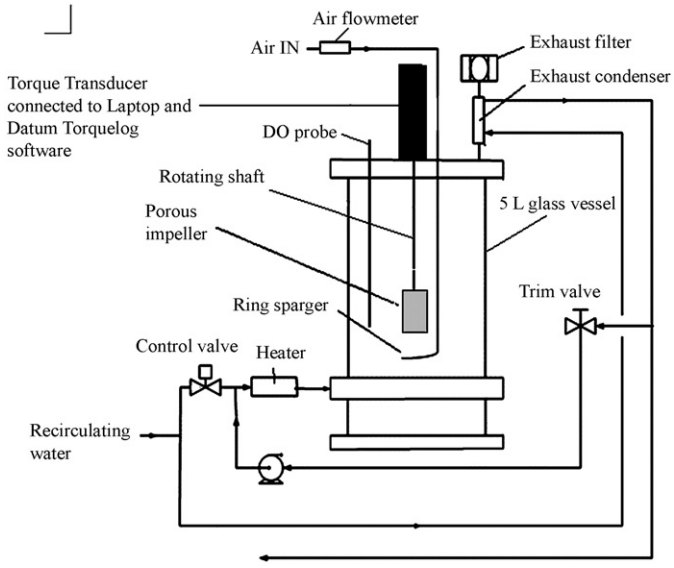

Fig. 1. Schematic of experimental set-up.

Fig. 2. Declon© mesh.

Fig. 4. Knitted stainless steel wire mesh.

ature and agitation in the reactor module allowed the operating conditions in the reactor to be automatically controlled. Compressed nitrogen and air were supplied via a sparging ring with four small holes located at the bottom of the vessel. Aeration rates were controlled by a flow meter. The torque and power consumed by each impeller system were measured by a torque meter (Datum Electronics, UK) mounted on the shaft outside the vessel. Random repeat measurements showed that power measurements were found to be reproducible within ±5%.

2.2. Mass transfer experiments

A range of porous packing materials mounted onto the shaft in the vessel were tested for their mass transfer performance in the oxygen transfer process from air to water and air to a 50% (v/v) glycerol in water mixture and their corresponding power consumption. The materials used were Declon© (PVC rigidised polyurethane foam) (110 mm diameter, 6 layers each of 10 mm thickness mounted onto the shaft and held in place by top and bottom support plates), compacted fibre mesh (110 mm diameter, 4 layers each of 15 mm thickness attached to shaft and held by support plates) and knitted stainless steel wire mesh (105 mm diameter, 40 mm height) as shown in Figs. 2–4. Tests under identical conditions of aeration rate and agitator speed were also performed with two conventional six-bladed Rushton turbine impellers (6 cm diameter, blade dimensions: 18 mm × 17 mm, 6 cm apart on the shaft) (Fig. 5) to enable comparison between the mesh impellers and the conventional impeller to be made. It is to be noted that the intention with the porous impellers was to use them as a rotating packed bed of porous elements occupying a large cross-sectional area of the vessel, hence their larger diameter in comparison with that of the Rushton turbine which is of the order of $D_T/3$ as recommended in the literature [24]. Such a configuration makes the porous impellers similar in design to that of a bubble column having perforated trays fitted at regular intervals where the splitting of bubbles occurs throughout the whole cross-section of the column but with the additional flexibility of bed rotation in our present set-up.

All impellers were positioned on the shaft such that their bottom edge was located at a distance of 9 cm from the bottom of the vessel. Experiments were performed in deionized water and a Newtonian liquid mixture of water/glycerol (50%, v/v, of each component) at a controlled temperature of 35 °C.

The static method of gassing out [25], sometimes also referred to as the dynamic gassing out method [26], was employed to obtain the dissolved oxygen concentration profile as a function of time from which K_La was determined as a measure of the mass transfer rate of oxygen into the liquid medium. After calibration of the DO probe at 100 and 0% oxygen saturation using air and nitrogen, respectively, the liquid medium was first sparged with nitrogen until the oxygen content of the solution was reduced to zero. Air was then introduced at a set rate in the range 0.2–1.0 vvm with a selected impeller rotation rate between 200 and 1000 rpm. The DO concentration, denoted by C, was recorded as a function of time until the liquid medium was fully saturated. A typical DO profile for the static gassing out method is shown in Fig. 6.

Fig. 3. Compact fibre mesh.

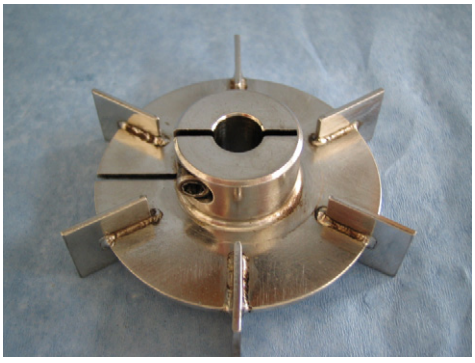

Fig. 5. Rushton turbine impeller.

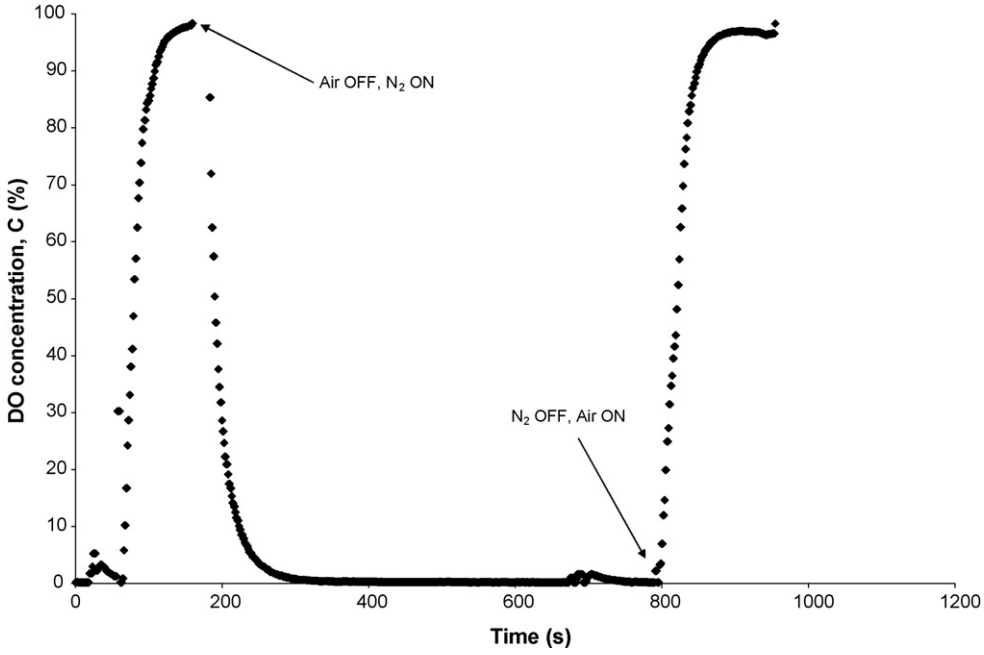

Fig. 6. DO profile using static gassing out method for calculating K_La.

2.3. Fermentation experiments

E. coli fermentations were performed in batch mode in the BioFlo III module using the double Rushton turbine impeller or the knitted wire mesh impeller shown in Fig. 4. The other mesh impellers could not be tested in the fermentation runs as the materials were not heat resistant enough to be autoclaved. Temperature was controlled at 35 °C. The effects of impeller configuration on cell growth profiles were tested with air flowrates of 1 and 1.25 vvm (equivalent to 4 and 5 L air/min, respectively, for a working volume of 4 L fermentation broth) and agitator speeds of 200, 300 and 400 rpm. The pH of the medium was set at 5.5–6.0 at the start of the fermentation run but was not controlled.

The fermentation broth was composed of distilled water with 20 g/L glucose; 5 g/L yeast extract; 3 g/L KH_2PO_4; 6 g/L Na_2HPO_4; 0.5 g/L NaCl; 2.0 g/L Casein Hydrolysate; 10 g/L $(NH_4)_2SO_4$.

A 4 L volume of the broth was charged to the vessel prior to autoclaving at 121 °C for at least 30 min. After the broth had cooled down to room temperature, 100 mL of post-sterilisation media was added after being filter-sterilised. This consisted of 0.5 g/L $MgSO_4{\cdot}7H_2O$, 0.0294 g/L $CaCl_2{\cdot}2H_2O$, 0.008 g/L thiamine, 40 mg/L $FeSO_4$, 20 mg/L citric acid and 0.5 mL/L of a mixture of trace elements. To control foaming, 0.4 mL of filtered polyethylene glycol was added to the medium.

A single colony of *E. coli* grown on nutrient agar was used to inoculate 40 mL of freshly sterilised medium. The shake flask culture which was left to grow overnight in a temperature controlled shaker set at 37 °C and 120 rpm was used to inoculate the 4L fermentation broth.

The dynamic gassing out method was used to estimate the oxygen uptake rate (OUR) by the micro-organisms and the K_La in the fermentation system as described later in the treatment of results.

The *E. coli* growth profile was determined for each set of fermentation conditions by collecting samples at regular intervals from the reactor for optical density analysis using a UV–vis spectrophotometer at a wavelength of 570 nm. The absorbance of the sample was used as a measure of the biomass concentration.

After each fermentation run, the porous impeller was thoroughly washed with water before its re-use to flush out any cells which might have adhered onto the surface of the wire mesh.

3. Results

3.1. Mass transfer experiments

As stated earlier, the volumetric mass transfer coefficient, K_La, was obtained from the static gassing out method whereby a typical DO profile is recorded as shown in Fig. 6. The uptake of oxygen into the liquid (denoted by C) after the air is switched back on following nitrogen sparging is recorded by the DO probe at selected time intervals until the system reaches saturation.

If, in the simplified case, the DO probe is considered to have a very fast response in comparison with the system K_La, Eq. (2) which is derived from the integration of Eq. (1) is applicable:

$$\ln\left(1 - \frac{C}{C^*}\right) = -K_L a t \tag{2}$$

or, if a normalised parameter, C_L, is used for the dissolved oxygen concentration in the liquid, where $C_L = (C^* - C)/C^*$:

$$\ln(C_L) = -K_L a t \tag{3}$$

which, on rearrangement, gives

$$C_L = \exp(-K_L a t) \quad (4)$$

$K_L a$ can simply be determined from the gradient of a straight line plot of $\ln(C_L)$ against t.

However, the average response time, τ_p, of the DO probe used in our study was measured as 35 s at 35 °C, giving a probe sensitivity k_p (where $k_p = 1/\tau_p$) of 0.029 s^{-1}. This is of the same order of magnitude as the $K_L a$ we would expect in our experiments under optimised operating conditions for selected impeller systems. Therefore, the relatively slow response of the probe is likely to introduce a significant delay in the DO measurement. This delay was accounted for in our measurements by applying a first-order probe response as used in previous studies [27,28]:

$$\frac{dC_p}{dt} = \frac{1}{\tau_p}(C_L - C_p) \quad (5)$$

which, on integration, substitution and re-arrangement, yields [28]:

$$C_p = \frac{1}{t_m - \tau_p}\left[t_m \exp\left(\frac{-t}{t_m}\right) - \tau_p \exp\left(\frac{-t}{\tau_p}\right)\right] \quad (6)$$

where C_p is a normalised parameter for the DO concentration measured by the probe and $t_m = 1/K_L a$.

The average mass transfer time t_m and thereby the average $K_L a$ for each experiment was obtained by applying the Goal Seek function in Microsoft Excel to match the measured value of C_p recorded at different time intervals by the probe during the experiment to the value calculated from Eq. (6).

We have estimated $K_L a$ using both the simplified Eq. (4) and the more rigorous expression (6) which accounts for the probe response time. We note that, in general, for slow mass transfer (i.e. a mass transfer time $t_m > 100$ s), there is negligible difference in the $K_L a$ determined by each method. Nevertheless, the $K_L a$ data we present for the mass transfer experiments are all based on Eq. (6) for consistency. Random repeat experiments showed that $K_L a$ data were reproducible to within ±20%.

3.2. Air/water experiments

In order to verify the accuracy and consistency of our experimental data, we have first compared our results for the double Rushton turbine impeller with published $K_L a$ correlations obtained in pure water for single Rushton turbine impellers developed by Van't Riet [26] (Eq. (7)) and for multiple Rushton turbine impellers developed by Nocentini et al. [29] (Eq. (8)):

$$K_L a = 0.026\left(\frac{P}{V}\right)^{0.4} U_s^{0.5} \quad (7)$$

$$K_L a = 1.5 \times 10^{-2}\left(\frac{P}{V}\right)^{0.59} U_s^{0.55} \quad (8)$$

The comparison plots are shown in Fig. 7a and b. The dashed lines in Fig. 7a are representative of ±40% accuracy limits as indicated by Van't Riet [26]. Although there is some scatter of our experimental data points around the correlation plots,

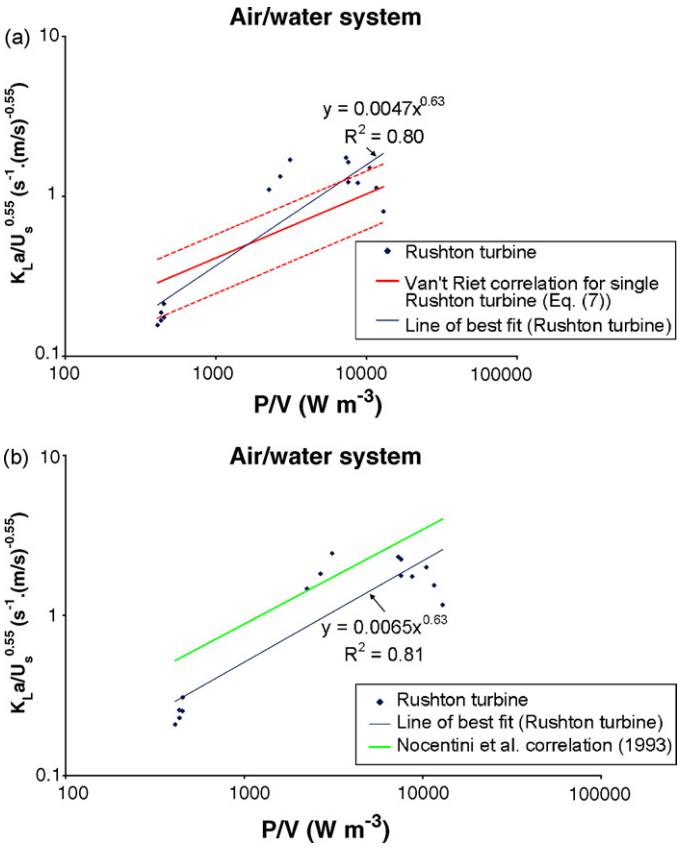

Fig. 7. (a) Comparison of Rushton turbine data with Van't Riet correlation for air/water system. (b) Comparison of Rushton turbine with Nocentini et al. correlation for air/water system.

it is seen that they, nevertheless, fit reasonably well with each correlation and are mostly within the deviation limits. It is also evident from the line of best fit through our experimental data on each plot that our results follow the correlation developed by Nocentini et al. [29] very closely since the slope of line of best fit is almost identical to that of the correlation in Fig. 7b. The $K_L a$ correlation for the double Rushton turbine from the present study be therefore may described as:

$$K_L a = 6.5 \times 10^{-3}\left(\frac{P}{V}\right)^{0.63} U_s^{0.55} \quad (R^2 = 0.81) \quad (9)$$

This correlation also agrees reasonably well with that developed by Arjunwadkar et al. [30] for a double Rushton turbine impeller system.

The mass transfer performance of the Declon© mesh impeller in water and its corresponding power consumption are shown in Figs. 8 and 9, respectively. As expected, a steady increase in $K_L a$ with impeller speed and aeration rate is observed. Increasing agitator speed results in a large increase in power consumption whilst increasing the aeration rate at constant agitator rate causes a slight decrease in power consumed as the liquid system becomes less dense. Similar trends were observed for all the impellers tested.

When the mass transfer performance in water of each of the porous agitators are compared with that of the more commonly used Rushton turbine impeller at 1 vvm aeration rate (Fig. 10),

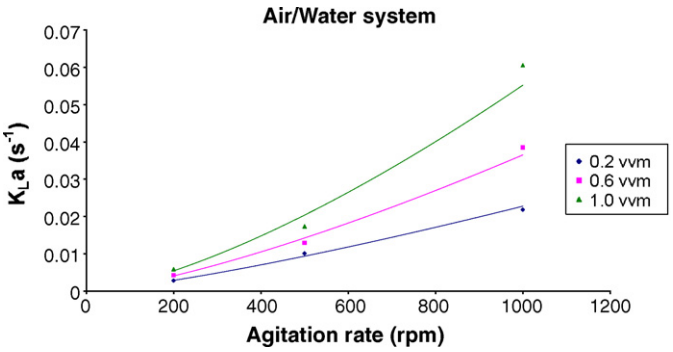

Fig. 8. Effect of aeration rate and impeller speed on oxygen transfer rate for a Declon© mesh impeller in deionized water.

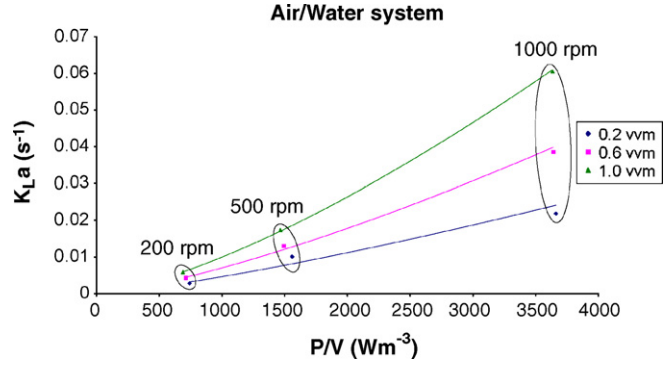

Fig. 9. Comparison between $K_L a$ and power consumption for Declon© mesh impeller in deionized water for a range of aeration rates and impeller speeds.

it is clear that the double Rushton turbine is a more efficient agitator than the Declon© or the fibre mesh elements, especially in the low power density region. Fig. 10 would also seem to suggest that at higher power input the Declon© mesh element may give a higher mass transfer performance that the Rushton turbine. It is notable, however, that the double Rushton turbine is outperformed by the knitted wire mesh over the 200–400 rpm range of agitator speeds tested for the latter system. The mass transfer enhancement with the knitted wire mesh may be explained by its intricately wound filaments breaking up large gas bubbles into fine bubbles as the bubbles rise from the sparger and pass through the mesh element. As the smaller bubbles travel up

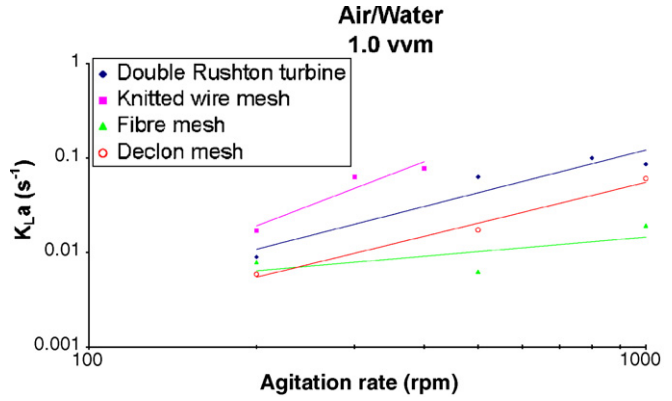

Fig. 10. Comparison of $K_L a$ for all impellers in air/water system at 1 vvm aeration rate.

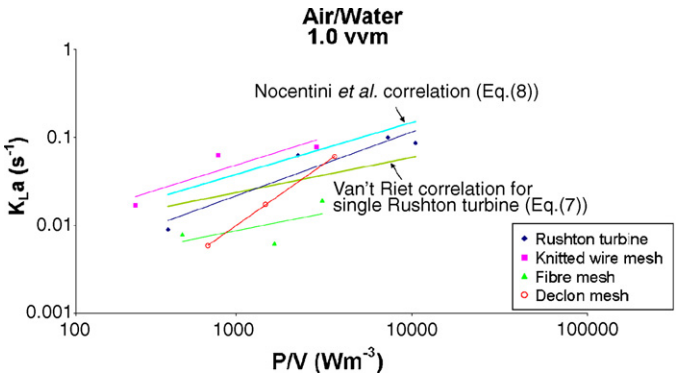

Fig. 11. Comparison of $K_L a$ and power consumption for all impellers in air/water system at 1 vvm aeration rate.

through the mesh which occupies a relatively large proportion of the vessel volume, the chances of these bubbles coalescing are minimised. We have visually observed consistently smaller bubbles being formed and dispersed throughout the vessel when the knitted wire mesh is used in comparison with the Declon© or the fibre mesh elements. A study is currently underway to measure the size of the bubbles formed and their distribution in each of the porous impellers to confirm the proposed argument.

We have also evaluated the mass transfer performance of each of the porous mesh elements under consideration in relation to the average gassed power input into the liquid per unit volume, P/V as shown in Fig. 11 for a selected aeration rate of 1 vvm. Literature correlations from Van't Riet and Nocentini et al. are also included for comparison. It is again evident from Fig. 11 that the knitted wire mesh gives the best mass transfer performance at any given power consumption compared to the other systems investigated in this study or indeed even compared to the literature correlations. In relation to the double Rushton turbine performance, this seems to suggest that the knitted wire mesh uses the power input more efficiently to promote mass transfer rather than being dissipated in vortex formation as would be expected with the Rushton turbine especially at high agitation rates. We noted a drop in the $K_L a$ measured with the Rushton turbine at 1000 rpm for all aeration rates tested (as seen in Fig. 10), which we believe may be attributed to vortex formation in the system at such high agitator speeds. During experiments, visual observation indeed confirmed that above 800 rpm a vortex was formed in the vessel when the Rushton turbine was used, in spite of the presence of baffles in the vessel. The vortex cavities tend to cause flooding and reduce impeller performance. Thus, a large amount of power is dissipated in vortex formation. It is interesting to note that no vortex was apparent with any of the mesh impellers used in this study. However, due to the lack of visibility into the mesh structures, it is not known whether flooding occurred.

Similar $K_L a$ enhancements with the knitted wire mesh are observed at all aeration rates as seen in Fig. 12 where the best line fit through all the knitted wire mesh experimental data in pure water is of the form:

$$K_L a = 8.5 \times 10^{-3} \left(\frac{P}{V}\right)^{0.71} U_s^{0.55} \quad (R^2 = 0.92) \tag{10}$$

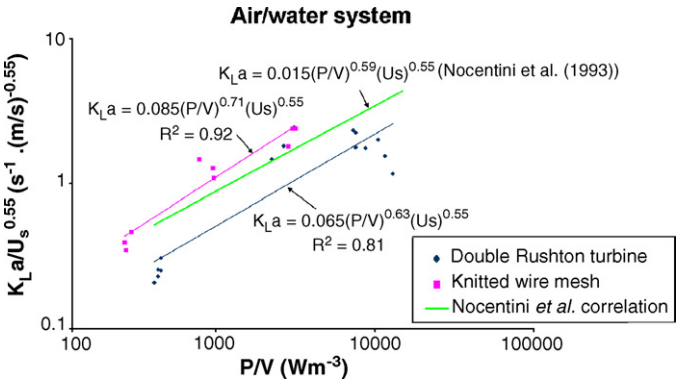

Fig. 12. Comparison of Rushton turbine and knitted wire mesh data with literature correlation in air/water system at all aeration rates.

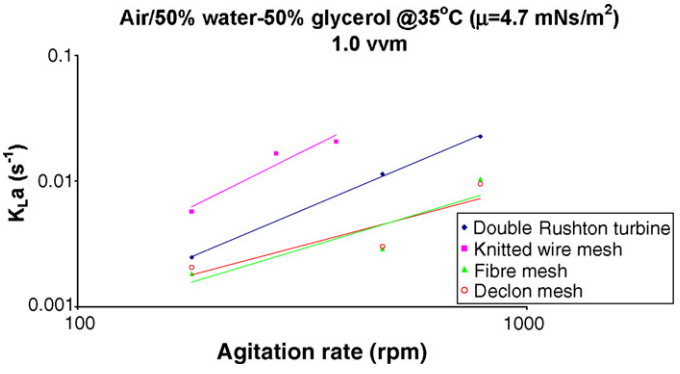

Fig. 13. Comparison of K_La in air/50% water–50% glycerol (v/v) system for all impellers at 1 vvm aeration rate.

3.3. Air/water/glycerol experiments

The mass transfer performances of each of the porous mesh elements in a mixture of 50% (v/v) water/50% glycerol mixture (viscosity = 4.7 mNs/m^2 at 35 °C) are compared with the double Rushton turbine impeller in Figs. 13 and 14 at an aeration rate of 1 vvm. The knitted wire mesh gives consistently higher mass transfer coefficients at a given power input in comparison with all the other impeller types under the range of operating conditions tested. For example, at 1 vvm aeration rate, the mass transfer capability of the knitted wire mesh impeller at 1000 W/m^3 is more than double that of the Rushton turbine, with K_La of 0.012 s^{-1} for the knitted wire mesh and 0.0045 s^{-1} for the Rushton turbine (Fig. 14). This enhancement effect of the knitted wire mesh is observed to be greater in the low power input region. Generally, it is seen that the Rushton turbine draws significantly more power (about three times more) in the more viscous liquid system to achieve similar mass transfer levels when compared to the knitted wire mesh impeller as indicated in Fig. 14 for a selected K_La of 0.01 s^{-1}. The high power consumption of Rushton turbine impellers is a well-recognised disadvantage of this type of impeller [30], especially in highly viscous, Non-Newtonian liquids [31]. Our data clearly indicate the intensification characteristic of the knitted stainless steel wire mesh in comparison with the Rushton turbine over the range of liquid viscosities studied. On the other hand, the compact fibre mesh and the Declon© impellers give poor performance in comparison with the Rushton turbine in the water/glycerol mixture system, although their performance seems to converge to that of the Rushton turbine at higher power input.

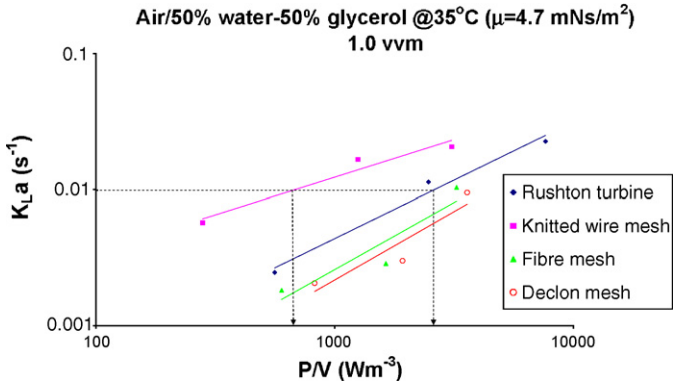

Fig. 14. Comparison of K_La and power consumption in air/50% water–50% glycerol (v/v) system at 1 vvm aeration rate.

An overall comparison between the knitted wire mesh and the Rushton turbine comprising data in the water/glycerol mixture under all operating conditions tested in this study can be made if we assume that the correlation derived by Nocentini et al. [29] for high liquid viscosity systems (Eq. (11)) is applicable:

$$K_La = C\left(\frac{P}{V}\right)^{0.62} U_s^{0.4}\left(\frac{\mu}{\mu_w}\right)^{-1.17} \quad (11)$$

The comparison plots shown in Fig. 15 indicate that the line of best fit for our double Rushton turbine data deviates quite significantly from the literature correlation presented by Nocentini et al. [29] for multiple Rushton turbines. It is thought that this is most likely due to the rather low viscosity of the mixture under consideration in our study (4.7 mNs/m^2) where as the literature correlation is based on a range of highly viscous mixtures (up to 62 mNs/m^2). Nocentini et al. indeed suggest that for lower

Table 1
Oxygen uptake rates (OUR), K_La and oxygen transfer rate (OTR) measured under various conditions of fermentation using Rushton turbine and knitted wire mesh impellers at aeration rate of 1.25 vvm

Impeller type	Agitation rate (rpm)	OUR (mol L^{-1} h^{-1})	K_La (s^{-1})	OTR (mol L^{-1} h^{-1})
Rushton turbine	200	0.019	0.00171	0.043
	400	0.122	0.00848	0.347
Knitted wire mesh	200	0.020	0.0053	0.146
	400	0.616	0.0236	0.802

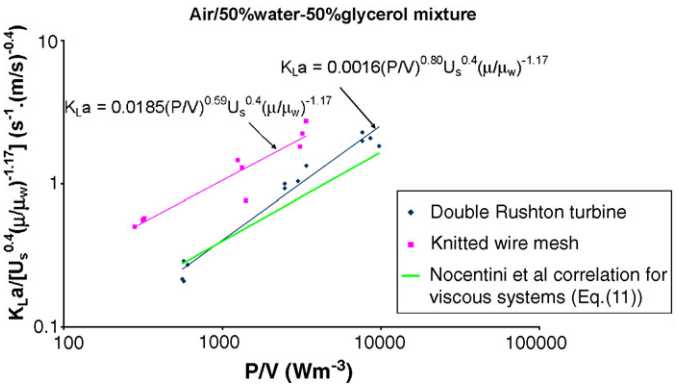

Fig. 15. Comparison of Rushton turbine and knitted wire mesh in air/50% water–50% glycerol (v/v) with literature correlation.

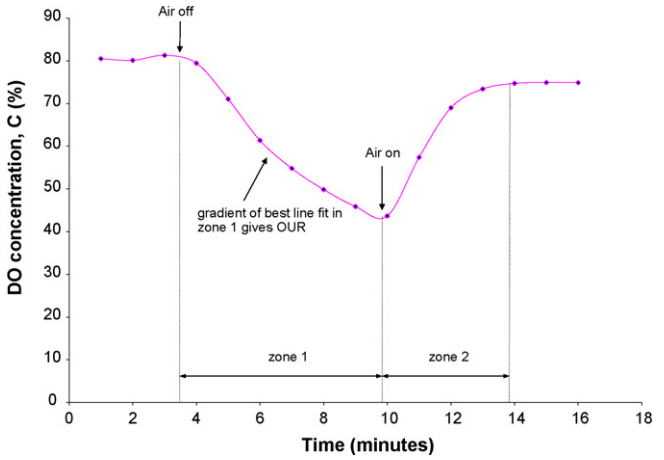

Fig. 16. DO profile using dynamic gassing out method for calculating OUR and K_La in fermentation system.

viscosity systems, the exponent of the viscosity term may be as low as −0.75 as opposed to the −1.17 value derived in their correlation.

A regression analysis on all the data collected for the Rushton turbine and the knitted wire mesh clearly shows that the exponent in the viscosity term in the correlations (Eqs. (12) and (13)) is close to the value of −0.75 suggested by Nocentini et al.

Ruston turbine:

$$K_La = 4.41 \times 10^{-3}\left(\frac{P}{V}\right)^{0.69} U_s^{0.55}\left(\frac{\mu}{\mu_w}\right)^{-0.71} \quad (R^2 = 0.91) \tag{12}$$

Knitted wire mesh:

$$K_La = 1.05 \times 10^{-2}\left(\frac{P}{V}\right)^{0.64} U_s^{0.52}\left(\frac{\mu}{\mu_w}\right)^{-0.68} \quad (R^2 = 0.95) \tag{13}$$

3.4. Fermentation experiments

Preliminary tests to evaluate the application of the porous agitator designs in real fermentation systems have been undertaken using *E. coli* as the micro-organism. *E. coli* was chosen as it is well studied and has a relatively high growth rate (typically $\mu = 2.0\,h^{-1}$) and a relatively rapid doubling time of 20 min [32] in comparison to other organisms.

The dynamic method of gassing out [25] was used to estimate the total oxygen uptake rate, OUR ($= Xq_{O_2}$), of the micro-organisms and the overall mass transfer coefficient K_La in the fermentation system. The supply of air was cut allowing the DO to fall for a short period of time and was then reconnected allowing the DO to reach a stable concentration. A typical DO profile obtained in our fermentation experiments is shown in Fig. 16.

The change in DO concentration (C) for a respiring culture where oxygen is continuously being supplied is given by Eq. (14):

$$\frac{dC}{dt} = K_La(C^* - C) - Xq_{O_2} \tag{14}$$

OUR ($= Xq_{O_2}$) is obtained from the slope of the straight line profile during the period when the air is switched off, indicated by zone 1 in Fig. 16.

Re-arrangement of Eq. (14) yields:

$$C = -\frac{1}{K_La}\left(\frac{dC}{dt} + Xq_{O_2}\right) + C^* \tag{15}$$

A plot of C versus $((dC/dt) + Xq_{O_2})$ for the period over which the DO concentration rises to reach steady state after the air is switched back on (zone 2 in Fig. 16) allows K_La to be calculated for the system from the gradient.

It is seen from Table 1 that the K_La measured by the dynamic gassing out method during the fermentation and the average oxygen transfer rate (OTR) in the vessel are higher for the knitted wire mesh at both agitation speeds. The K_La values determined from these fermentation experiments for both the Rushton turbine and the knitted wire mesh match those obtained under similar operating conditions for the 50% water/50% glycerol mixture, data for which have been presented earlier. This suggests that the viscosity in the fermentation media is close to 5 mNs/m^2.

The OUR values are also observed to be higher for the knitted wire mesh than for the Rushton turbine (albeit only very slightly higher at 200 rpm) indicating that the increased K_La plays an important part in supporting the growth of a larger number of cells for higher productivity. These results are in agreement with the improvement seen in the cell density profile when using the knitted wire mesh impeller (Fig. 17). Our results also indicate that cell growth proceeds under non-oxygen limiting conditions in the vessel both with the Rushton turbine and the knitted wire mesh since the OTR values calculated under the different conditions are consistently higher than the OUR. Also, the OUR in our experiments are of the same order of magnitude as the typical requirements of most fermentation systems which are in the 40–200 mmol $O_2\,L^{-1}\,h^{-1}$ range [1].

We have compared the effect on cell growth profile (measured in terms of absorbance or optical density) using the knitted wire mesh design and the double Rushton turbine impeller. Under aeration rates of 1.25 vvm, it was observed that the knitted wire mesh resulted in higher absorbance and therefore cell density at

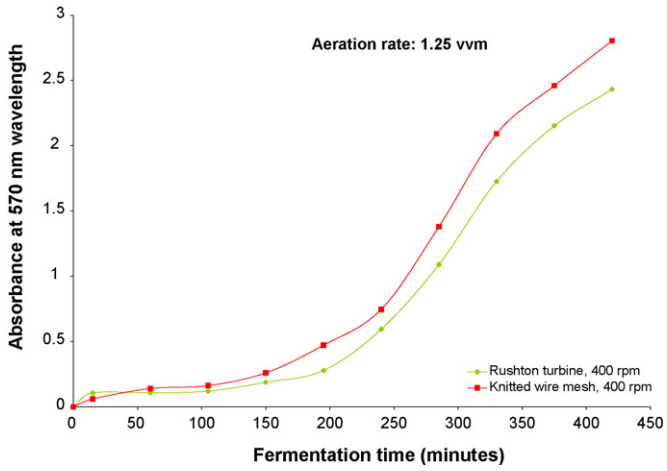

Fig. 17. Comparison of cell growth profiles using Rushton turbine and knitted wire mesh impellers.

the end of the 8 h fermentation period, giving a higher overall *E. coli* cell growth rate than the Rushton turbine at an agitator speed of 400 rpm (Fig. 17).

We therefore conclude from the preliminary fermentation experiments carried out in this study that the knitted wire mesh demonstrates promising potential for enhancing cell growth under high oxygen transfer rates. However, a more in-depth study into the fermentation application of the porous mesh elements is required to elucidate these enhancement effects.

It is worth mentioning that, in the reported work, we have not observed clogging of the porous structure of the knitted wire mesh by the growth of cells in the fermentation process. This may be because the operating conditions were not conducive to attaining a very high concentration of cells which may give rise to such a problem as a result of the natural tendency of micro-organisms to adhere to surfaces. The extent to which the porous elements may be blocked by high density cell cultures grown under appropriate operating conditions in batch mode is currently being studied and will be reported in a future publication.

4. Conclusions

In this study, a range of porous impellers have been characterised in terms of their mass transfer and power consumption in air/water and air/50% water–50% glycerol (v/v) mixture, representing liquid viscosities of 0.7 and 4.7 mNs/m^2, respectively. Preliminary fermentations experiments have also been conducted to evaluate the effect of the knitted wire mesh as an example of a porous impeller system on the cell growth profile of *E. coli*. Enhanced volumetric mass transfer coefficients K_La have been obtained using the knitted stainless steel wire mesh when compared with the double Rushton turbine in both the pure water and water/glycerol mixture. We believe that such enhancements are due to the filaments of the knitted wire mesh breaking up large gas bubbles into fine bubbles providing greater surface area for oxygen transfer into the liquid medium. High mass transfer to power consumption ratios observed with the knitted wire mesh, especially in the high viscosity liquid system, indicate its promising potential for mass transfer intensification under these conditions. In contrast, the mass transfer performance of the Declon© mesh and the fibre mesh packings were poor when compared to double Rushton turbine, especially in the range of low power densities. Preliminary evaluation in an *E. coli* fermentation system indicates that the knitted wire mesh gives a higher overall cell growth rate and potentially higher productivity which may be attributed to its higher oxygen transfer capability than the Rushton turbine.

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