

Oxygen mass transfer in a 16.6 cm i. d. multiphase reciprocating plate column

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Abstract: The effects of vibration intensity, superficial gas velocity and content of solid particles on the volumetric oxygen mass transfer coefficient (k_1a) in a 16.6 cm i.d. multiphase reciprocating plate column were studied. The k_1a increased with increasing vibration intensity and superficial gas velocity, and decreased with increasing content of solid particles. The k_1a was correlated with the specific time-averaged power consumption, the superficial gas velocity, the column diameter and the content of solid particles.

Keywords: reciprocating plate column, volumetric oxygen mass transfer coefficient, power consumption, superficial gas velocity, sulphite method.

INTRODUCTION

Reciprocating plate columns (RPCs) belong to the generation of novel reactors,¹ because of their efficient mass transfer. As a multiphase contacting device, RPC combine aeration and agitation, ensuring favorable hydrodynamic and mass transfer characteristics. RPCs have wide use in waste water treatment,² as well as the biosynthesis of extracellular polysaccharides^{3–5} and metabolites.⁶ As in the case of other contacting devices, the volumetric oxygen mass transfer coefficient (k_1a) is used to measure the oxygen mass transfer rate in RPCs.

The values of k_1a in RPCs depends on the vibration intensity (product of amplitude and frequency of reciprocating movement, Af), the superficial gas velocity, the physical characteristics of the liquid phase, the type and content of solid particles placed into interplate spaces and the column geometry (the column diameter, the number of the perforated plates, the hole diameter and the fraction of plate free area).^{7–9} With increasing vibration intensity at a constant aeration rate, the k_1a is

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enhanced over the whole range of vibration intensity, due to more effective mixing and more uniform dissipation of the external energy over the column height.^{8–14} The k_1a increases up to a maximum value with increasing superficial gas velocity at a constant vibration intensity, as a result of the higher energy which the gas phase passes to the liquid phase.^{8,11, 13–15} The influence of the superficial gas velocity is significantly lower at low vibration intensities.^{8, 12, 16–18} At higher vibration intensities, the dispersion is homogeneous, and the oxygen mass transfer depends mainly on the power input by the action of the agitator, which increases both the gas holdup and the interfacial area.¹⁶

There is no agreement among different investigators about the influence of the superficial liquid velocity on the mass transfer in RPCs. According to some authors, the superficial liquid velocity has no¹³ or only a very small^{11,12,17} influence on the mass transfer. Others have shown a strong influence of the superficial liquid velocity on k_1a .^{14,18} The effect of the superficial liquid velocity on k_1a depends strongly on the geometry of the RPC and the superficial gas velocity.¹⁹

The physical properties of the liquid phase have a strong effect on the oxygen mass transfer in RPCs. It is well known that k_1a decreases with increasing liquid viscosity.¹⁷ On the other hand, k_1a increases on addition of compounds which inhibit the process of bubble coalescence, such as non-electrolytes and alcohols.²⁰

The value of k_1a increases when solid particles are placed into the interplate spaces of RPCs, regardless of the type of solid particles (spheres^{8,9} or Rashig rings¹³). The effect of solid particles appears to be dependent on the column diameter. With increasing content of solid particles, the mass transfer is enhanced negligibly in a 2.54 cm i.d. column, while it increases significantly in a 9.2 cm i.d. column.⁹

The reciprocating plate geometry strongly affects k_1a , which decreases with increasing plate hole diameter.^{10,13} With increasing fractional free plate area, k_1a also decreases.^{10,17} The value of k_1a is enhanced when the number of perforated plates is increased, due to a more intensive transfer of external energy to the gas–liquid dispersion.^{8–10,17}

In previous studies, the oxygen mass transfer in two multiphase RPCs, having 2.54 and 9.2 cm i.d. with and without the presence of solid particles (spheres) in the interplate spaces,^{8,9} were investigated. In this work, the study of the oxygen mass transfer was expanded to a gas–liquid–solid RPC of larger diameter (16.6 cm i.d. column). The main goal was to investigate the effects of the operating conditions (vibration intensity, superficial gas velocity and content of solid particles) on k_1a . It was also planned to compare the oxygen mass transfer rate in RPCs of different diameter. Finally, the aim was to check whether a correlation connecting k_1a with the operating conditions could be derived for all three columns.

EXPERIMENTAL

The scheme of the experimental setup can be found elsewhere.²¹ The dimensions of the column and perforated plates, as well as the ranges of operating conditions are given in Table I. The RPC con-

sisted of a 16.6 cm i.d. glass tube and a set of 15 perforated plates fixed on a rod which moved up-and-down through the column. The perforated plates were mounted on the rod at equal distances (5.0 cm). The plate stack was driven by an electromotor (1.5 kW) and an excenter. The amplitude was constant (2.35 cm) in all experiments, while the vibration frequency was varied in the range from 0 to 6 Hz by a three-phase frequency regulator (Yaskawa, Model VS-606V7). The gas phase (air at room temperature) was fed into the column by a compressor and a regulating valve (the average value of the pressure was 200 mbar) through four nozzles (nozzle diameter 1.5 mm) at the column bottom. The gas flow rate was regulated by a needle valve and measured by rotameters (Medingen, Dresden).

TABLE I. Geometric characteristics of the RPC and operating conditions

Column diameter (internal), cm	16.6
Column height (total), cm	153
Dispersion height, cm	97
Working volume, dm ³	20.87
Number of plates	–
Plate diameter, cm	16.15
Hole diameter, cm	0.78
Plate thickness, cm	0.12
Fractional plate free area, %	46.6
Spacing, cm	5.0
Length of tie-rod, cm	10.3
Amplitude of plate reciprocation, cm	2.35
Vibration frequency, Hz	2–6
Superficial gas velocity, cm/s	0.5, 1.0 and 1.5

The superficial gas velocity was 0.5, 1.0 or 1.5 cm/s. The static pressure of the gas near the rotameter was measured by a digital manometer (Laser, Leskovac, Serbia). An aqueous solution of sodium sulphite (0.8 M) and polypropylene spheres (density 930 kg/m³ and diameter 8.35±0.05 mm) were used as the liquid and solid phase, respectively. The spheres were placed in each interplate space (the solids content: 3.8 and 6.6 %, that is 190 and 321 particles per interplate space, respectively). These contents of solid particles were shown to enable the maximum gas holdup in a RPC.²²

The instantaneous pressure at the column bottom was measured by a differential pressure transducer (–50 to +50 kPa; IHTM, Model TPr–100.05, Belgrade, Serbia), connected *via* an amplifier and an A/D converter to a PC. The instantaneous power consumption was calculated from the instantaneous pressure variation at the column bottom and the instantaneous plate velocity:²³

$$P = \Delta p A_c u_s \quad (1)$$

The time-averaged power consumption was calculated by integration of the instantaneous power consumption over a definite time period as follows:

$$P_{av} = \frac{1}{T} \int_0^t |P| dt \quad (2)$$

The sulphite oxidation method was used for the determination of $k_1 a$. The value of $k_1 a$ was calculated from the maximum oxygen adsorption rate and the oxygen solubility in an aqueous solution of sodium sulphite:

$$k_1 a = r_{o,\max}/c_0 \quad (3)$$

The oxygen absorption rate was experimentally measured by means of sodium sulphite oxidation in the presence of copper sulphate as a catalyst.⁹ An aqueous solution of sodium sulphite (0.8 M) was prepared in a separate vessel by dissolving the predetermined mass of sulphite in distilled water. The initial pH of the solution was adjusted to 8.5 by adding a NaOH solution (5 M). Then, a concentrated solution of copper sulphate (0.1 M) was added and properly mixed, so that the final catalyst concentration was 10^{-4} M. This sulphite solution was transported into the RPC. The sulphite concentration was determined iodometrically in the initial sulphite solution and in a sample of the solution taken from the middle of the column after a certain period of time (10 to 20 minutes). The oxygen solubility in 0.8 M sodium sulphite solution was used in this calculation instead of the unmeasurable oxygen solubility in the sulphite solution; the former was calculated from an empirical equation based on the sulphate concentration and temperature of the sulphite solution.²⁴

The gas hold-up was measured by a method based on the direct measurement of the liquid volume, retained in the column after the gas flow was stopped and the electromotor was switched off. The height of the void fraction of the column was previously correlated to the volume of liquid drawn off from the column. The height of the dispersion was held constant in all test runs. The gas hold-up was calculated as the volume of the dispersed gas, divided by the total volume of the dispersion.²³

RESULTS AND DISCUSSION

The dependence of $k_1 a$ on the vibration intensity at two contents of solid particles and three different superficial gas velocities is shown in Fig. 1. With increasing of both the vibration intensity and the superficial gas velocity, $k_1 a$ increased, due to the enhanced break-up of bubbles and the enhanced gas hold-up, respec-

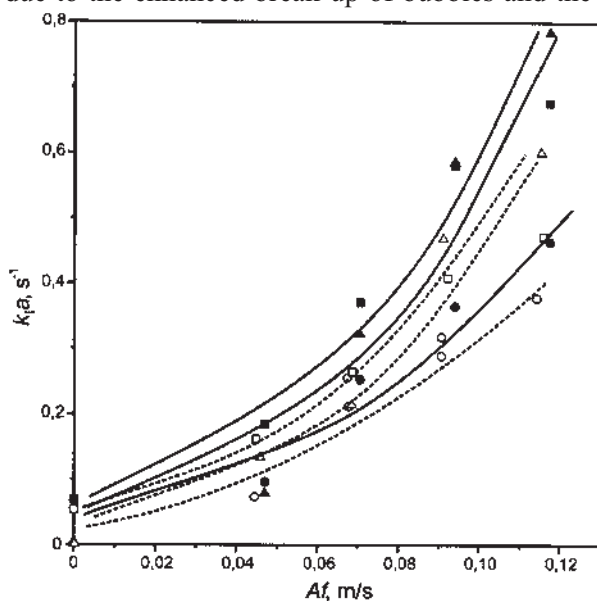


Fig. 1. Dependence of $k_1 a$ on the vibration intensity (ϵ_s , % by volume: 3.84 – full line; and 6.6 – dashed line; u_g , cm/s: 0.5 – circle; 1.0 – triangle; and 1.5 – square).

tively. At higher vibration intensities (approximately higher than 6 cm/s), the action of the perforated plates primarily affected the oxygen mass transfer. The solid particles in the interplate spaces also influenced the oxygen mass transfer in the RPC. When the content of solid particles was increased from 3.8 to 6.6 % by vol-

ume, k_1a decreased. It was found earlier that the same increase in the content of solid phase did not significantly affect k_1a in RPCs of smaller diameter (2.54 and 9.2 cm),⁹ despite the increase of the gas hold-up with increasing content of solid particles.²²

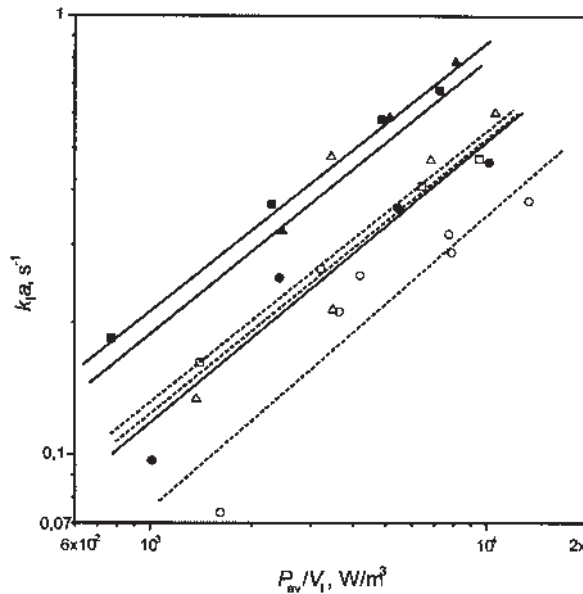


Fig. 2. Dependence of k_1a on the specific time-averaged power consumption (ϵ_s , % by volume: 3.8 – open symbols and 6.6 – solid symbols; u_g , cm/s: 0.5 – circle; 1.0 – triangle; and 1.5 – square; gas-liquid system – dashed line).

It is known that the time-averaged power consumption strongly depends not only on the vibration intensity but also on the content of solid particles, increasing with increasing content of solid particles.⁸ Thus, it is better to use the time-averaged power consumption than the vibration intensity to combine the effects of solid particles and vibration intensity on the oxygen mass transfer rate. The dependence of k_1a on the specific power consumption at different superficial gas velocities and contents of solid particles is shown in Fig. 2. This confirmed earlier observations that k_1a decreased with increasing content of solid particles at a specific power consumption and superficial gas velocity. A recent study showed that a decrease of the specific interfacial area was responsible for the negative influence of solid particles on k_1a at higher contents.²⁵ Figure 2 also shows that k_1a is exponentially proportional to the specific time-averaged power consumption, independent of the superficial gas velocity and the content of solid particles. This result indicated that k_1a could be correlated with the power consumption and the superficial gas velocity, as was already done to two RPC of smaller column diameter.⁹ For the 16.6 i.d. RPC, the following correlations were derived for solid phase contents of 3.8 and 6.6 % by volume, respectively:

$$k_1a = 0.0097 \left(\frac{P_{av}}{V_1} \right)^{0.786} u_g^{0.586} \quad (4)$$

and

$$k_1 a = 0.0112 \left(\frac{P_{av}}{V_1} \right)^{0.560} u_g^{0.326} \quad (5)$$

The values of the coefficient of linear correlation were 0.99 and 0.98, and the relative standard deviations were ± 10.8 and ± 5.8 for contents of solid particles of 3.8 and 6.6 % by volume, respectively. These data indicate a good agreement between the calculated and experimentally determined values of $k_1 a$. The values of the exponents in equations (4) and (5) showed that the action of the reciprocating

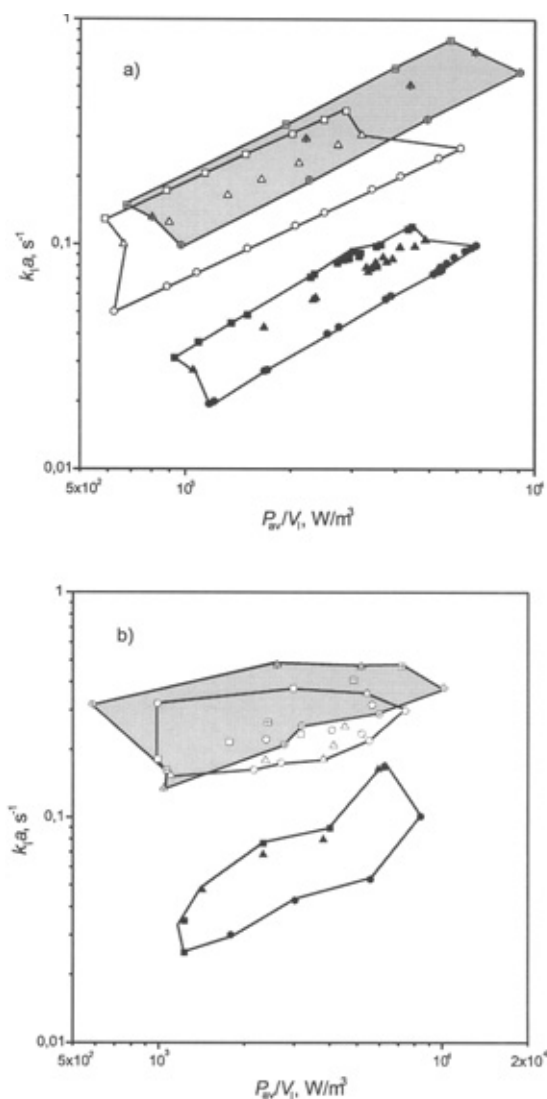


Fig. 3. Dependence of $k_1 a$ on the specific power consumption in three-phase RPCs with solid particle contents of a) 3.8 % and b) 6.6 % [u_g , cm/s: 0.5 – circle; 1.0 – triangle; and 1.5 – square; column diameter, cm: 2.54¹² – solid symbols; 9.2⁹ – open symbols; and 16.6 (present work – dark area) – (+) centered symbols].

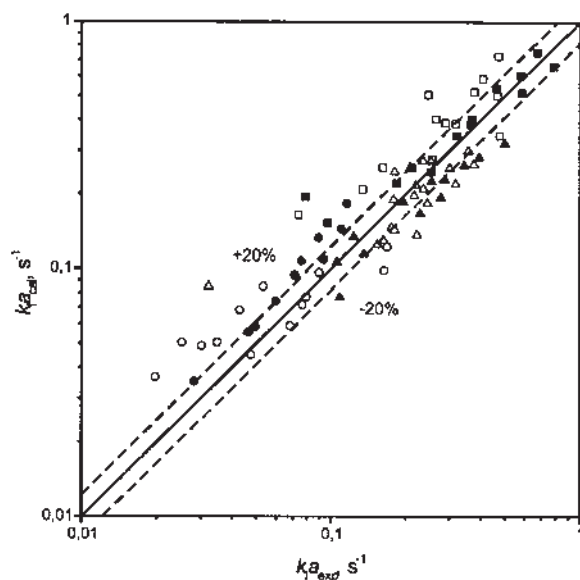


Fig. 4. Comparison of the calculated (Eq. (6)) and experimentally measured values of k_1a (ϵ_s , %: 3.8 – open symbols; and 6.6 – solid symbols; D_c , cm: 2.54 – circle; 9.2 – triangle; and 16.6 – square).

agitator was more important of oxygen mass transfer than the aeration rate. Previously, it was reported that the power consumption and the superficial gas velocity had the same influence on k_1a .⁹

It seemed appropriate to compare the oxygen mass transfer in RPCs of different geometries with respect to the major factors, that is the specific power consumption and the superficial gas velocity. The influence of the column geometry on the oxygen mass transfer rate can be seen in Fig. 3, where the dependence of k_1a on the specific time-averaged power consumption in gas–liquid–solid RPCs are shown. It is obvious that k_1a increase with increasing both the specific power consumption and the superficial gas velocity in the ranges from 600 to 9,000 W/m³ and 0.5 to 1.5 cm/s, respectively. The lowest value of k_1a was found in the column of the smallest diameter (2.54 cm), and the highest value was detected in the largest column (16.6 cm), regardless of the content of solids. It can be observed that the areas covering the data for the two larger columns (9.2 and 16.6 cm i.d.) overlapped. The following correlation for k_1a applicable for these three RPCs was derived:

$$k_1a = 0,073 d_k^{0,88} \epsilon_s^{-0,326} \left(\frac{P_{av}}{V_1} \right)^{0,544} (u_g)^{0,473} \quad (6)$$

The coefficient of linear correlation and the relative standard deviation were 0.90 and $\pm 19.8\%$ (number of data: 71) for the contents of solid particles of 3.8 and 6.6 % by volume. Figure 4 indicates a good agreement between the calculated and experimentally determined values of k_1a in the 2.54, 9.2 and 16.6 cm i.d. RPC.

CONCLUSIONS

In this work, the effects of the vibration intensity, superficial gas velocity and content of solids on k_1a in a 16.6 cm i.d. gas-liquid-solid RPC were investigated. It was established that k_1a increased with increasing vibration intensity and superficial gas velocity and with decreasing content of solid particles. For a constant content of solid particles, k_1a was correlated with the specific power consumption and the superficial gas velocity.

Based on a comparison with earlier studies, it was shown that k_1a also increased with increasing diameter of the RPCs. For the applied operating conditions and three RPCs of different diameter (2.54, 9.2 and 16.6 cm), a correlation connecting the volumetric oxygen mass transfer coefficient with the specific power consumption, the superficial gas velocity, the content of solid particles and the column diameter was derived. This correlation could be used for scaling-up the RPC types of contacting devices.

SIMBOLS

- A_c – Cross column area, m²
 A – Amplitude of the vibration, m
 a – Specific interfacial area, m²/m³
 Af – Vibration intensity, m/s
 c_o – Oxygen solubility, mol m⁻³
 f – Frequency, Hz
 k_1 – Mass transfer coefficient, m/s
 k_1a – Volumetric oxygen mass transfer coefficient, s⁻¹
 Δp – Instantaneous pressure drop at the column bottom, kPa
 Δp_{av} – Time-averaged pressure drop at the column bottom, kPa
 P – Instantaneous power consumption, W
 P_{av} – Time-averaged power consumption, W
 (P_{av}/V_1) – Specific time-averaged power consumption, W/m³
 $r_{o,max}$ – Maximum oxygen absorption rate, mol m⁻³ s⁻¹
 t – Time, s
 u_g – Superficial gas velocity, m/s
 u_s – Instantaneous plate velocity, ms⁻¹

Greek letters

- ε – Plate free area
 ε_g – Gas hold-up
 ε_s – Solid phase content
 ρ_1 – Liquid phase density, kg/m³

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ИЗВОД

ЗАПРЕМИНСКИ КОЕФИЦИЈЕНТ ПРЕНОСА МАСЕ КИСЕОНИКА У
ВИШЕФАЗНОЈ КОЛОНИ СА ВИБРАЦИОНОМ МЕШАЛИЦОМ ПРЕЧНИКА
16,6 cm

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У раду је испитиван утицај интензитета вибрација, привидне брзине струјања гаса и удела чврстих честица на запремински коефицијент преноса масе кисеоника у вишефазној колони са вибрационом мешалицом пречника 16.6 cm. Запремински коефицијент преноса масе кисеоника се повећава са повећањем интензитета вибрације и привидне брзине струјања гаса. Повећање удела чврстих честица у међупросторима између плочица утиче на смањење запреминског коефицијента преноса масе кисеоника. Изведене су емпиријске корелације које повезују запремински коефицијент преноса масе кисеоника са специфичном средњом снагом мешања и привидном брзином струјања гаса за различите уделе чврстих честица.

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