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Chemical Engineering Journal 68 (1997) 29–33

Chemical Engineering Journal

Overall volumetric oxygen transfer coefficient and optimal geometry of airlift tube reactor

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Received 20 June 1996; revised 11 March 1997; accepted 2 June 1997

Abstract

Absorption of oxygen from air into distilled water in a new type of airlift tube reactor has been investigated at the 1.3 l scale. Results of this mass transfer study together with hydrodynamic results provide a means of optimizing the geometrical parameters of the reactor. The overall volumetric oxygen transfer coefficient (K_La) was measured as a function of the gas velocity in reaction tubes, the liquid hold-up in the reactor expressed in terms of liquid height, the cross-sectional area ratio of the recycle-to-reaction tubes (A_{rec}/A), the liquid temperature and specific power input. The K_La was measured using a dynamic gassing method with polarographic measurements of dissolved oxygen. © 1997 Published by Elsevier Science S.A.

Keywords: Airlift tube reactor; Oxygen mass transfer; Optimal geometry

1. Introduction

Airlift reactors are a special class of pneumatic reactors which currently are receiving much attention for application to various reactor and fermentation systems. Their self-generated liquid circulation give them added advantages, for example improved heat transfer [1], mass transfer and mixing compared to bubble columns and conventional stirred tank reactors [2–4].

The overall volumetric oxygen transfer coefficient (K_La) is frequently the basis of comparing and evaluating different reactor designs intended for gas–liquid mass transfer applications. The K_La coefficient is based on the concept that the liquid film is the controlling resistance to mass transfer. This assumption is reasonable for oxygen transfer in gas–liquid contacting systems [2–4].

The phenomenon of oxygen transfer from air bubbles to liquid has been studied and reported by many investigators. However, most of the earlier works were generally carried out either in one size or type of reactor only, or just one or two of the several operation and design parameters were investigated [4]. Results on overall volumetric oxygen transfer coefficients in various types of air-lift reactors are comprehensively compiled in Chisti's book [4]. K_La may be enhanced by addition of small amounts of methanol or ethanol [5], or by using static mixers in the reaction tubes [6].

2. Mathematical model of oxygen transfer

The following mathematical model was used to describe the dynamic behaviour of the reactor and the probe:

$$\frac{dC}{dt}=K_La(C^*-C) \tag{1}$$

The reactor and the probe were considered to be first-order elements. This assumption was confirmed by measurements.

2.1. Dynamic behaviour of the reactor

The effective number of totally mixed units (N) for the reactor was obtained by the residence time distribution method using impulse disturbance with concentrated sodium chloride solution. The measurements were carried out at air velocities (v_G) in the range 1.77–7.07 m s^{-1}, at a constant temperature (T) of 25 ± 1°C, liquid volume (V) of 1 l and an area ratio (A_{rec}/A) of 0.25.

Using air and distilled water at normal operation conditions, concentrated sodium chloride solution was injected into the liquid inlet. The conductivity of salt water in the outlet

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PII S1385-8947(97)00067-3

was followed by a conductivity meter connected to a potentiometeric recorder.

The number of totally mixed units was calculated on the basis of a linearized impulse–response equation by the least-squares method. The calculated number of totally mixed units varied in the range of 1.086–1.145. The measured time constants (T_1) of the reactor were in the range 10.1–47.6 s.

2.2. *The time constant (T_2) of the probe*

The time constant of the probe was measured directly as follows. Two water-containing glass beakers, 1 and 2, were both thermostated in a constant temperature (T= 15, 25 or 35°C). The level of dissolved oxygen in beaker 1 was held at zero using Na_2SO_3 solution with cobalt chloride as the catalyst for oxygen consumption. The water in beaker 2 was saturated with dissolved oxygen by continuous bubbling with air. The oxygen probe YSI 5730 (5) was equilibrated in beaker 1. Upon stabilization, the probe was rapidly transferred to beaker 2. The step change in oxygen concentration was followed with an oxygen meter (YSI 59) connected to a personal computer.

Using a linearized first-order transit equation and the least-squares method, the probe was established to be a first-order element. The time constant (T_2) of the probe depended on the thickness and the age of the membrane and on water temperature. The constant was checked every time when the membrane was changed. At different water temperatures (T= 15, 25 and 35°C) the T_2 values were in the range of 8.3–16 s.

2.3. *Dynamic model of the reactor–probe system*

If the time constant of the probe is negligible in comparison with the time constant of the reactor, the probe practically does not take part in the dynamic process: hence, the reactor and probe system can be regarded as a first-order element. If the value of the time constant of the probe is comparable with that of the reactor, as was the case in our work, the reactor and probe have to be considered a second-order system.

The equation which represents the output response of the second-order system subjected to a step change disturbance is [7]:

$$y=A_1A_2a\left[1-\frac{1}{T_1-T_2}(T_1e^{-t/T_1}-T_2e^{-t/T_2})\right] \tag{2}$$

Although the change of oxygen concentration in the system is [4]:

$$C=C^*\left[1-\frac{1}{T_1-T_2}(T_1e^{-t/T_1}-T_2e^{-t/T_2})\right] \tag{3}$$

Besides the concentration response curve, the time constant (T_2) of probe must be measured separately. With this the time constant (T_1) of reactor can then be calculated. From T_1 the K_La was obtained using the following relation [5]:

$$K_La=\frac{1}{T_1} \tag{4}$$

3. Experimental work

The aim of measurements was to determine the K_La values of the reactor for different total liquid hold-up and geometrical and operation parameters. Details of the equipment used are shown in Fig. 1. The main parts of the airlift tube reactor and its operation have been described previously [8,9]. The dissolved oxygen was measured with a YSI 5730 probe. An air/distilled water system was used. The water was introduced into reactor (1) from water tank (13) by peristaltic pump (9) through the liquid feeding line (8). The mixing and heating in the reactor were performed by blowing compressed air into the reactor through an air line (18), and warm water from the thermostated reservoir (15) into the jacket of the reactor (7). The air flow-rate was measured by an air rotameter (17).

In normal operation, the air pressed the liquid into four reaction tubes and a gas–liquid two-phase mixture rose up in them. The absorption took place in the reaction tubes (4) of 270 mm length and 10 mm inside tube diameters. The liquid recycled into the downcomer part of the reactor in one recycle tube (6) of 120 mm length and different diameters. The operation was continuous with respect to gas and batch wise with respect to liquid.

Three recycle tube diameters, 7, 10 and 14 mm, were tested to give A_{rec}/A ratios of 0.1225, 0.250 and 0.490, respectively. The experimental conditions covered the following ranges: water temperature of 15–35°C, air velocity in the reaction tube of 1.77–7.07 m s^{-1} and the liquid volume of 0.85–1.3 l (= liquid height of 136–237 mm). The oxygen analyzer was standardized at experimental temperature before each run. Zero percent oxygen was fixed with a saturated solution of sodium sulphite catalyzed with cobalt chloride, while 100% oxygen point was adjusted with oxygen-saturated water.

The overall volumetric mass transfer coefficient (K_La) was calculated from Eq. (4). The time constant of the reactor (T_1) depended on the temperature and was strongly influenced by the geometrical and operation conditions of the reactor.

The temperature of the distilled water was 15, 25 or 35°C. As soon as the liquid in the reactor reached the desired temperature, the sodium sulphite solution catalyzed with cobalt chloride was added through the liquid feeding line (8) until the dissolved oxygen concentration of water became almost 0 mg l^{-1}. The experiment run started when all sodium sulphite had been consumed. The experiment was stopped when the dissolved oxygen concentration reached a constant saturated value C^*. The liquid from the reactor was discharged via discharge point (14) and the reactor was filled with fresh water for the next experiment.

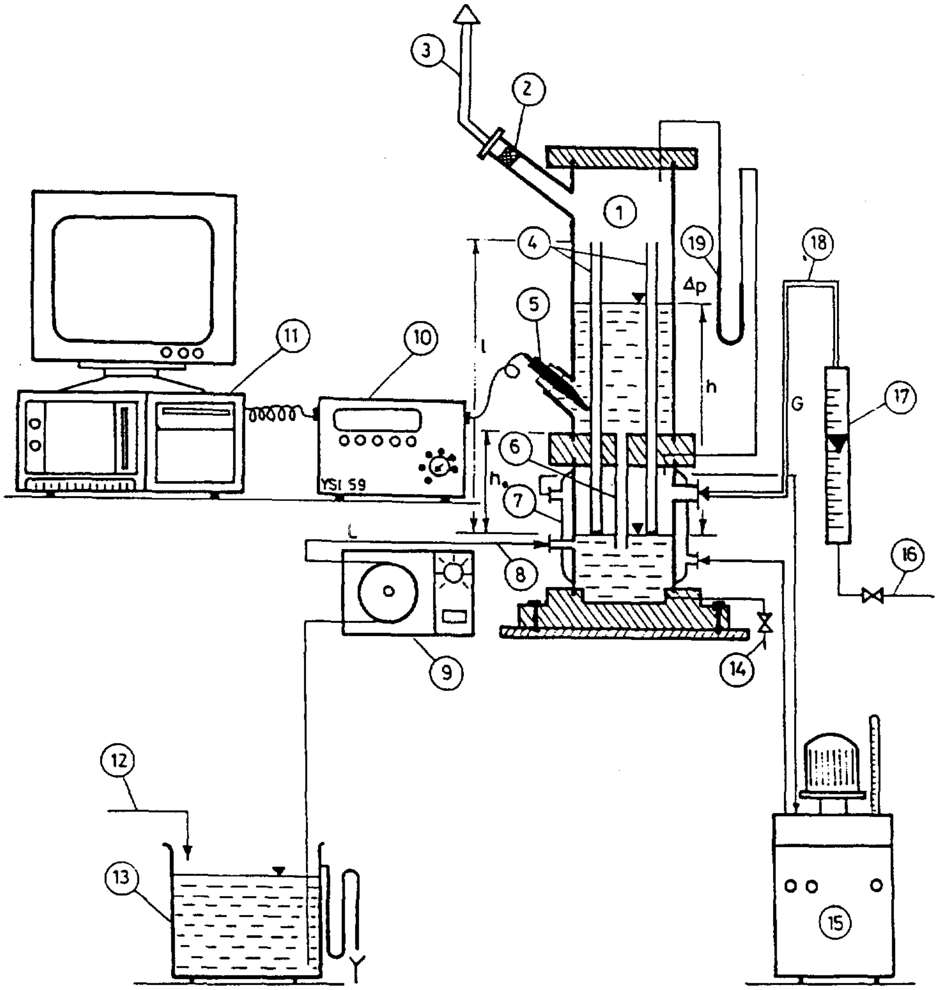

Fig. 1. Experimental apparatus: 1,. Airlift tube reactor; 2, mist eliminator; 3, exhaust air line; 4, reaction tubes; 5, dissolved oxygen probe; 6, recycle tube; 7, water jacket; 8, distilled water and $Na_2SO_3 + CoCl_2$ input; 9, peristaltic pump; 10, oxygen meter; 11, personal computer; 12, distilled water; 13, distilled water tank; 14, liquid drain; 15, thermostated water reservoir; 16, compressed air; 17, air rotameter; 18, air feed line; 19, water manometer.

The time constant of the reactor T_1 was determined from Eq. (3) using the measured value of T_2. The measured time constants (T_1) were in 10.1–47.6 s range.

4. Results and discussion

Figs. 2–4 represents the influence of gas velocity (v_G), area ratio (A_{rec}/A) and water temperature (T) on the overall volumetric oxygen transfer coefficient (K_La). The coefficient increased with an increase in v_G, A_{rec}/A and T. Several investigators measured similar influences of gas velocity (v_G), liquid hold-up (V) and liquid temperature (T) on (K_La) in other types of airlift reactors. The K_La increases with an increase in v_G [5,10–12] and with an increase in T [13], while K_La decreases with an increase in V [5,12]. The K_La strongly increases with an increase in liquid temperature as was previously established in the literature [13].

A correlation was developed for the airlift-tube reactor as a function of operation and geometric variables:

$$\mathrm{St}=0.0028\left(\frac{P}{V}\right)^{0.21}\left(\frac{h}{h_o}\right)^{-0.55}\left(\frac{A_{rec}}{A}\right)^{-0.76}\left(\frac{T}{T_o}\right)^{0.80} \qquad (5)$$

Eq. (5) is valid in the range of $300<P/V<2100$; $1.13<h/h_o<1.98$; $0.1225<A_{rec}/A<0.49$; $1<T/T_o<2.33$. The equation correlated more than 100 data within ±20%. The influence of specific power input (P/V) was moderate, while the liquid height ratio (h/h_o), the area ratio (A_{rec}/A) and the water temperature ratio (T/T_o) had a significant influence on K_La. Voigt and Schügerl [5] published K_La data for the bubble column. The range of specific power input (P/V) and its exponent n for distilled water were $100<P/V<1200$ and $n=1.2$ for 1 and 3 mm sparger plates and $1.2<n<1.85$ for a 0.5 mm plate. Schügerl [14] developed correlation for a stirred tank reactor, where K_La was expressed as a function of P/V. The composition of the liquid affected the constant but not the exponent n. The values of n were in the range 0.38–0.58, depending on the type of agitator.

The optimal A_{rec}/A values were determined on the basis of the specific power input per unit mass transfer coefficient (P/K_La). Fig. 5 represents (P/K_La) as a function of gas velocity (v_G) for different area ratios and liquid heights. The area

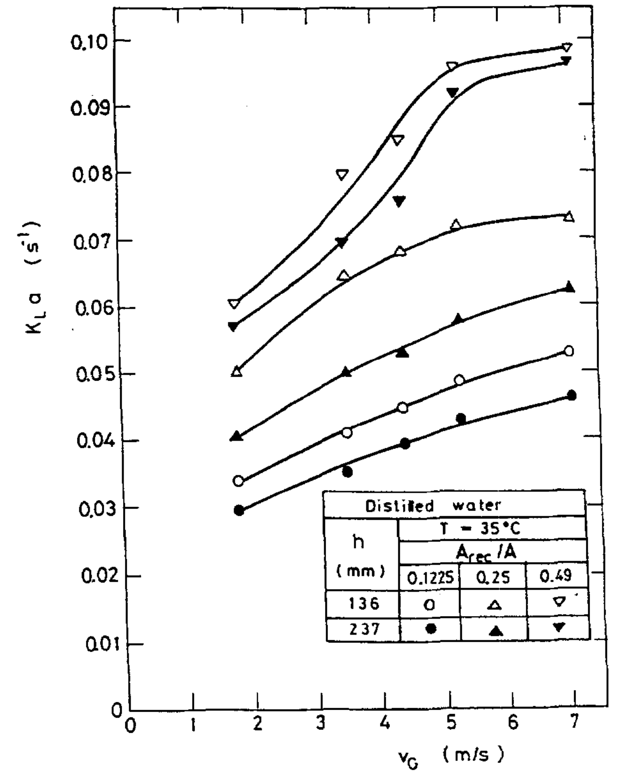

Fig. 2. Influence of gas velocity (v_G) on the overall volumetric mass transfer coefficient (K_La).

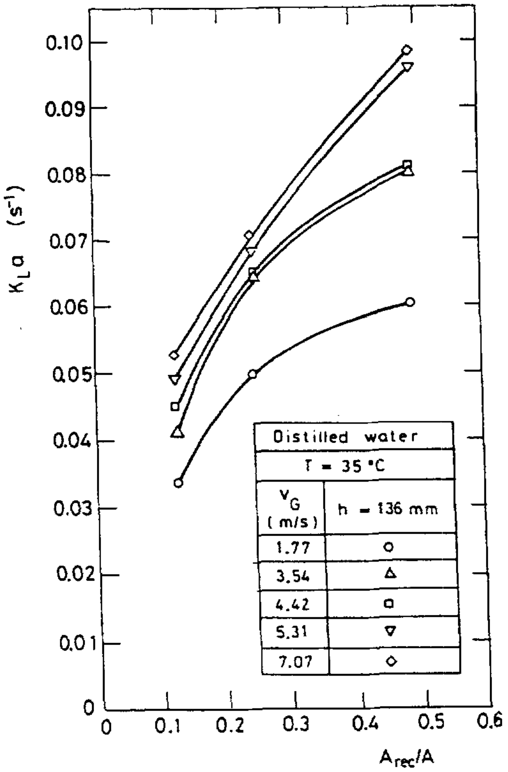

Fig. 3. Influence of area ratio (A_{rec}/A) on the overall volumetric mass transfer coefficient (K_La).

ratio (A_{rec}/A) of 0.25 was chosen as an optimal arrangement, because the power input is moderate and the gas–liquid mass transfer area is about twice as high as in the case of the higher

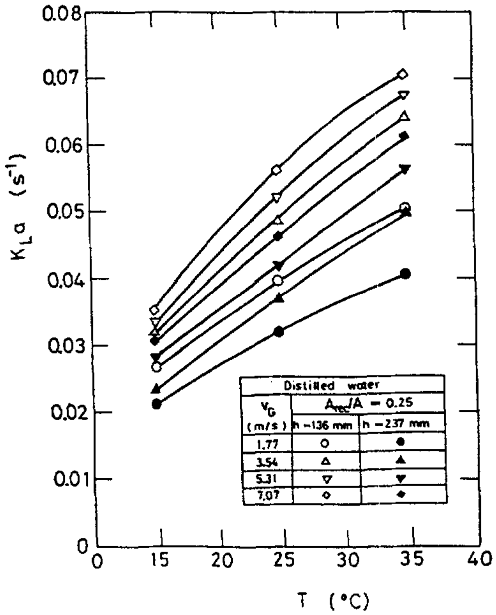

Fig. 4. Influence of water temperature (T) on the overall volumetric mass transfer coefficient (K_La).

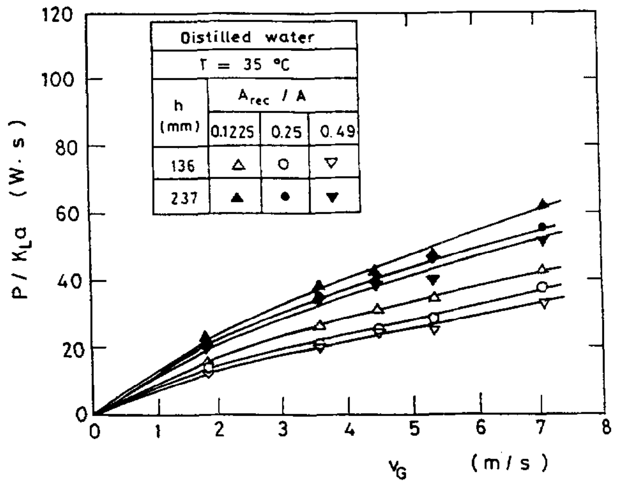

Fig. 5. The power input per overall volumetric mass transfer coefficient (P/K_La) as a function of gas velocity (v_G).

ratio ($A_{rec}/A = 0.49$). Values of K_La at $A_{rec}/A = 0.12$ were unfavourable.

The airlift tube reactor was successfully scaled up with design correlations discussed above [8,9] by keeping constant the value of A_{rec}/A at 0.25. The gas load was increased from 0.1 $m^3 h^{-1}$ to 1400 $m^3 h^{-1}$ using several reaction tubes in parallel [15].

5. Nomenclature

Note: In the text and figures some of the variables are also expressed in commonly used dimensions.

a	amplitude of step change in input variable
A	cross-sectional area of all reaction tubes (m^2)
A_1	gain of reactor
A_2	gain of probe

A_{rec}	cross-sectional area of recycle tube (m)
C	concentration of oxygen in liquid phase (mg l^{-1})
C^*	concentration of oxygen in liquid phase at saturation (mg l^{-1})
G	inlet gas load ($\mathrm{m}^3\ \mathrm{s}^{-1}$)
h	liquid height (m)
h_o	minimum liquid height (m), $h_o = 0.09$ m
K_La	overall volumetric oxygen transfer coefficient in liquid phase based on the total liquid volume in the reactor (s^{-1})
l	length of reaction tube (m)
L	inlet liquid load ($\mathrm{m}^3\ \mathrm{s}^{-1}$)
P	power input, $P = \Delta pG$ (W)
Δp	pressure drop in reaction tube (Pa)
St	Stanton number in the reaction tube, $\mathrm{St} = K_La \cdot l / v'_L$
t	time (s)
T_1	time constant of reactor (s)
T_2	time constant of probe (s)
T	liquid temperature (°C)
T_o	minimum liquid temperature (°C)
v_G	superficial gas velocity in reaction tube (m s^{-1})
v_L	liquid velocity in the recycle tube (m s^{-1})
v_L'	superficial liquid velocity in the reaction tube, $v'_L = v_L \cdot A_{\mathrm{rec}}/A$
V	total liquid hold-up in the reactor (m^3)

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