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Liquid–solid mass transfer behaviour of a fixed bed airlift reactor

A.A. Harraz [a], I.A. El Gheriany [a], M.H. Abdel-Aziz [a,b,*], T.M. Zewail [a], A.H. Konsowa [a], G.H. Sedahmed [a]

[a] Chemical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt
[b] Chemical and Materials Engineering Department, Faculty of Engineering, King Abdulaziz University, Rabigh 21911, Saudi Arabia

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ABSTRACT

The liquid–solid mass transfer behaviour of a fixed bed of Raschig rings placed in the riser or the downcomer of a rectangular airlift reactor was studied by a technique involving the diffusion controlled dissolution of copper in acidified dichromate. Variables studied were superficial gas velocity, ring diameter, bed height and physical properties of the solution. The mass transfer coefficient was found to increase with the 0.425 exponent of the superficial gas velocity, at relatively high superficial gas velocity a limiting mass transfer coefficient was reached. The mass transfer coefficient was found to decrease slightly with increasing bed height, ring diameter was found to have a little effect on the rate of mass transfer. The data were correlated for fixed beds placed in the riser and fixed bed placed in the downcomer by dimensionless equations involving the groups *J*, Re and Fr. Comparison of the present data with previous studies on sparged fixed beds confirmed the superiority of packed bed airlift reactors to packed bubble column reactors. A natural convection mathematical model was found to explain the mechanism of mass transfer at the fixed bed airlift reactor. The importance of the present reactor in conducting diffusion controlled liquid–gas–solid biocatayltic and catalytic reactions, and electrochemical reactions was highlighted.

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1. Introduction

In view of the attractive features of airlift reactors, such as the simple design (no moving parts), low shear rate, low energy consumption, high mixing efficiency, uniform temperature distribution and low capital and operating costs, the reactor has been receiving growing attention in research and industry. The superiority of airlift reactors to bubble column and mechanically stirred reactors has led to their increasing use in processes, such as chemical, biochemical, petrochemical, waste water treatment and hydrometallurgy; recently their use has been extended to electrochemical processes [1].

Airlift reactor consists of a gas sparged riser and a downcomer which are connected at the top and the bottom to allow circulation between the two compartments in order to increase the degree of turbulence and hence the rate of mass transfer in the riser.

Previous studies on airlift reactors [2–7] have concentrated on the hydrodynamic aspects and gas–liquid mass transfer especially mass transfer of O_2 in aqueous solutions in relation to biochemical processes. Little has been done on the liquid–solid mass transfer behaviour of such reactors despite the importance of the subject in case of liquid–gas–solid catalytic reactions which are controlled by the liquid–solid mass transfer step. Such a study would assist in designing airlift bioreactors containing packed bed of immobilized enzyme catalyst and microorganisms used to conduct diffusion controlled bioreactions, such as the following examples: production of saccharides [8–10], bioethanol production [11–16], removal of phenols and other organic pollutants from wastewater [17–22], and removal of hexavalent chromium [23,24]. The present reactor can be used also to enhance the rate of mass transfer between the liquid reactant and the fixed enzyme even when air is not involved in the reaction, i.e. in this case airlift is used as a low cost means of stirring [25]. The use of fixed bed airlift reactors can be extended to other areas, such as diffusion controlled liquid–gas–solid photochemical and electrochemical reactions involving three phase systems, such as H_2O_2 production by the cathodic reduction of atmospheric O_2 [26] and flue gas desulphurization by anodic oxidation of SO_2 to H_2SO_4 [27]. Moreover, fixed bed airlift reactors obviate the shortcomings of the competing slurry airlift reactors (fluidized bed) such as catalyst attrition, low slip velocity of the catalyst particles and the high cost of separating the final product from the catalyst particles.

* Corresponding author at: Chemical and Materials Engineering Department, Faculty of Engineering, King Abdulaziz University, Rabigh 21911, Saudi Arabia. Fax: +20 3 59211853.
E-mail address: helmy2002@gmail.com (M.H. Abdel-Aziz).

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List of symbols

A	Bed active area, cm^2
a, a_1, a_2, a_3	Constants
C	$K_2Cr_2O_7$ concentration at any time, M
C_o	Initial concentration of $K_2Cr_2O_7$, M
D	Diffusivity, $cm^2\,s^{-1}$
d	Diameter of the cylindrical reactor, cm
d_e	Equivalent diameter of the rectangular reactor, cm
d_r	Raschig ring diameter, cm
e	Specific energy dissipation, $cm^2\,s^{-3}$
g	Acceleration due to gravity, $cm\,s^{-2}$
k	Mass transfer coefficient, $cm\,s^{-1}$
t	time, s
Q	Volume of working solution, cm^3
V_g	Superficial gas velocity, $cm\,s^{-1}$
V_L	Superficial liquid velocity, $cm\,s^{-1}$
Fr	Froude number $\left(\frac{v_g}{gd_r}\right)$
Gr	Grashof number $\left(\frac{gd_r^3}{\nu^2}\frac{\Delta\rho}{\rho}\right)$
J	Mass transfer J factor ($J = St \times Sc^{0.66}$)
Re	Reynolds number $\left(\frac{\rho V_g d_r}{\mu}\right)$
Re_L	Reynolds number $\left(\frac{\rho V_L d_r}{\mu}\right)$
Sc	Schmidt number $\left(\frac{\nu}{D}\right)$
Sh	Shrewood number $\left(\frac{kd_r}{D}\right)$
St	Stanton number $\left(\frac{k}{v_g}\right)$
ϵ	Gas holdup
μ	Solution viscosity, $g\,cm^{-1}\,s^{-1}$
ν	Kinematic viscosity, $cm^2\,s^{-1}$
ρ	Solution density, $g\,cm^{-3}$
$\bar{\rho}$	Average density of gas–liquid dispersion, $g\,cm^{-3}$
ρ_g	Gas density, $g\,cm^{-3}$

The aim of the present work is to study the mass transfer behaviour of a fixed bed of Raschig rings placed in the riser or in the downcomer of a rectangular airlift reactor. Previous studies have used fixed beds only to improve the rate of gas–liquid mass transfer [2–7] but no study has been reported on liquid–solid mass transfer at fixed bed in airlift reactors. As far as we know two previous studies on liquid–solid mass transfer in airlift reactors deserve to be mentioned. Mao et al. [28] studied the liquid–solid mass transfer behaviour of a fluidized bed airlift reactor using a technique which involves the dissolution of benzoic acid particles in the solution. The authors found that at relatively low superficial gas velocity the mass transfer coefficient was unaffected, beyond certain gas velocity the mass transfer coefficient increased with increasing gas superficial velocity. Abdel-Aziz et al. [1] using electrochemical technique studied the mass transfer behaviour of the wall of the downcomer of a concentric tube airlift reactor with the aim of using airlift reactors for conducting diffusion controlled gas–liquid–solid electrochemical reactions and developing a heat transfer equation (by analogy) which predicts the rate of heat transfer to a cooling jacket surrounding the reactor. The present study was conducted using a technique which involves the diffusion controlled dissolution of copper in acidified dichromate [29,30], the technique has been used widely to study liquid–solid mass transfer in view of its simplicity and accuracy [31–35]. The technique does not suffer from the drawback of the benzoic acid technique which produces exaggerated mass transfer coefficient owing to particle attrition, the present technique also does not suffer from the problem of current distribution inherent with the electrochemical technique in case of fixed beds.

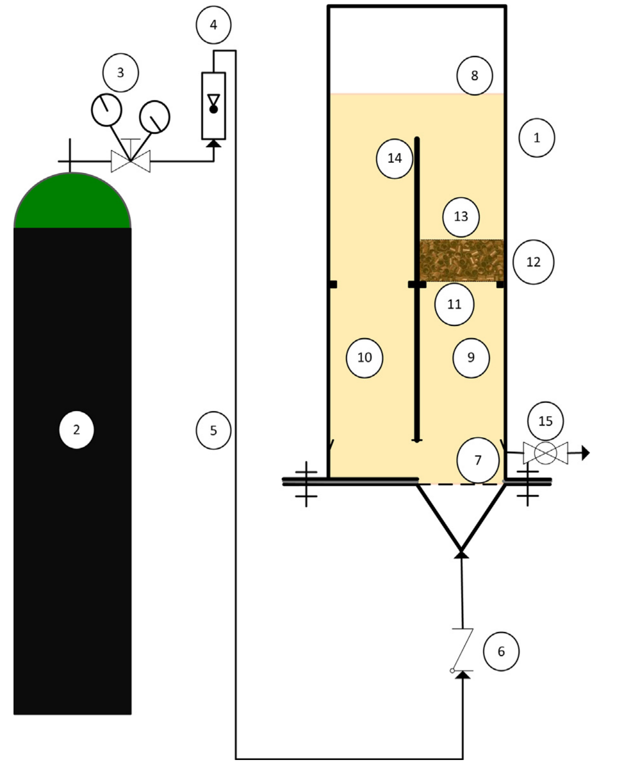

Fig. 1. A schematic diagram of the experimental setup.
(1) Air-lift reactor, (2) nitrogen gas cylinder, (3) pressure regulator with screw-down valve, (4) calibrated rotameter, (5) 8 mm PVC tubing, (6) non-return valve, (7) G2 sintered glass gas sparger, (8) liquid level in the air-lift reactor, (9) riser, (10) downcomer, (11) insulated stainless steel support, (12) Raschig rings fixed bed, (13) insulated stainless steel strainer, (14) baffle, (15) drain valve.

2. Experimental technique

The apparatus (Fig. 1) consisted of a plexiglass rectangular container of the dimensions 15 cm × 7.5 cm for the base and 50 cm height. The container was divided into two similar compartments by a plexiglass vertical baffle of 36 cm height place at 4.5 cm from the base of the container, each compartment (the riser and the downcomer) had the dimensions 7.5 × 7.5 cm for the base and 50 cm height (i.e.) the ratio between the cross sectional area of the riser and the downcomer was 1. The base of the riser was replaced by a G2 sintered glass gas sparger (40–100 μm pore size). The sintered glass was fitted to the container bottom by a flanged joint. The sintered glass surface was glued to a coplanar plastic flange by epoxy resin, this flange was connected to the container flange by a number of insulated stainless steel bolts, a rubber gasket was placed between the two flanges to prevent solution leakage. The sintered glass has a conical bottom through which N_2 was admitted to the sintered glass distributor. A bed of randomly packed copper Raschig rings supported by epoxy coated stainless steel screen was located either in the riser or the downcomer at a distance 26 cm from the base, the stainless steel support rested on four plastic pins glued to the four walls of the riser or the downcomer. The bed active area ranged from 912 cm^2 to 2736 cm^2 depending on the particle size and the bed height (Table 1). Three different Raschig ring diameters were used, namely 0.635, 0.953 and 1.27 cm, bed porosity was 76%, 81% and 90%, respectively. Four bed heights were used, namely 3.81, 6.35, 8.89, 12.7 cm.