Full Papers

Volumetric Mass Transfer Coefficient of Oxygen in an Internal Loop Airlift Reactor with a Convergence-Divergence Draft Tube

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Experimental measurements of hydrodynamics and the volumetric mass transfer coefficient of oxygen (VMTCO) in an internal loop airlift reactor with different types of draft tubes are reported for the two-phase systems, air/water and air/carboxyl methyl cellulose (CMC) solution, and a three-phase system, air/water/resin particle, respectively. The properties of convergence-divergence draft tubes with three different structural parameters are compared with those of the conventional column draft tube. The results indicate that gas holdups in convergence-divergence draft tubes are higher than those in conventional draft tubes, the volumetric mass transfer coefficient of oxygen increases with increasing superficial air flow rates. The convergence-divergence draft tubes all show higher mass transfer capacity than the traditional ones. A 10% higher mass transfer coefficient is observed for the three structural parameters. In the air/CMC system, the volumetric mass transfer coefficient of oxygen decreases with increasing bulk viscosity, while in the three-phase system VMTCO increases with the resin particle loading. The correlation equation of the volumetric mass transfer coefficient with the operating conditions and structural parameters is established.

1 Introduction

Airlift reactors are known to be efficient contractors for the chemical process and biotechnology industries [1]. Their relatively simple mechanical design, high capacity, good mixing, low cost, low power input, and low shear stress make them a versatile type of reactor. There are many variations of airlift reactors; however, two broad types of such reactors need to be distinguished and can be further subdivided into other categories: 'internal' and 'external' loop reactors. Detailed descriptions of each type and its sub-categories can be found in the book [2]. An airlift reactor consists of a riser and a downcomer that are interconnected near the top and the bottom of the reactor. Hydrodynamics (gas holdup, liquid circulation velocity) and mass transfer coefficients are the most important parameters used in assessing airlift reactors. And hydrodynamics and mass transfer are inextricably linked in airlift reactors. These parameters are sensitive to gas velocity and physical properties of the fluids, and reactor geometry. The fluidized-bed reactor as one kind of airlift reactor has brought much attention to the technology. The results from laboratory and field pilot scale studies have consistently illustrated the technical advantages of the fluidized-bed reactor over most other suspended and supported growth biological reactor configurations in the treatment of water and wastewater [3]. Some researchers have dealt with hydrodynamics and mass transfer in fluidized-bed reactors [4–5]. Recently, more and more investigations have been focused on hydrodynamic aspects and mass transfer

enhancement of airlift reactors. To improve gas-liquid mass transfer performance, the introduction of divided draft tubes, perforated plates, or static mixers into the reactors has been extensively examined. Generally, these kinds of measures can help to promote continuous renewal of the gas-liquid interfacial area and thorough contact of gas phase and liquid phase. Although these measures improve gas-liquid mass transfer in some degrees, there are limitations and disadvantages in some aspects to wastewater treatment processes. Malik and coworkers [6] proposed the use of a convergence-divergence draft tube to replace the conventional draft tube, this change in configuration can help the broth to converge and diverge continuously, it is expected to promote continuous renewal of the gas-liquid interfacial area and thorough contact of gas phase and liquid phase. Thus it can help to increase the volumetric mass transfer coefficients of the reactors for a particular air flow rate, consequently, to achieve a particular dissolved oxygen concentration and to satisfy the oxygen uptake rate of a particular microbiological system at a lower energy consumption.

Many researches have dealt with hydrodynamics and mass transfer in airlift reactors including two-phase and three-phase systems [7–10]. In our previous study [11], hydrodynamics in an internal loop airlift reactor with a convergence-divergence draft tube was investigated. The objective of this work is to examine its volumetric mass transfer coefficient of oxygen (VMTCO). A comparison on mass transfer between three different convergence-divergence draft tubes and one conventional draft tube in internal airlift reactor is provided. The correlation of the volumetric mass transfer coefficient, which takes into account the effects of the most important parameters (e.g. operating conditions, liquid properties, different structural parameters etc.) on the performance of the airlift reactor, is presented.

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2 Experimental

2.1 Reactor Design

The schematic diagram for the measurement of hydrodynamics and the volumetric mass transfer coefficient is depicted in Fig. 1, and the dimensions of the standard cylindrical draft tube and the convergence-divergence draft tubes are reported in Tab. 1. As seen from Fig. 1, the apparatus mainly consists of air supply system, bulk reactor system and measurement system. Among them, the reactor is made up of organic glass for its transparency with an approximated volume 16.8 L, 860 mm in height and 80 mm in internal diameter. Fig. 2 is the schematic structural diagram of the draft tube.

Figure 1. Experimental setup for an internal loop airlift reactor: 1 – reactor, 2 – downcomer, 3 – sparger, 4 – rotameters, 5 – feed tank, 6 – air compressor, 7 – water tank, 8 – gas-liquid separator, 9 – valve, 10 – CMC solution, 11 – pump, 12 – oxygen probe, 13 – oxygen meter, 14 – recorder, 15 – microcomputer, 16 – printer, 17 – conductivity meter, 19 – liquid drainage, 20 – U-type manometer.

Figure 2. Structural diagram of convergence-divergence draft tubes.

2.2 Phase Description

The experimental media used were water (or CMC solution), air, and resin particles. The two-phase system consists of water/air or CMC solution/air, and the three-phase system consists of water/air/resin particles. The air flow rate

Table 1. Dimensions of the draft tubes.

No. of draft tube	L_c (mm)	L_d (mm)	h (mm)	r_c (mm)	r_d (mm)	r^* (mm)	$\tan\alpha_c$	$\tan\alpha_d$
conventional draft tube (No. 1)	/	/	0	30.4	30.4	30.4	0	0
convergence-divergence draft tube (No. 2)	75.8	75.5	5.0	25.5	30.5	28.0	0.0660	0.0662
convergence-divergence draft tube (No. 3)	99.9	48.9	4.9	25.3	30.2	27.8	0.0490	0.1002
convergence-divergence draft tube (No. 4)	50.5	102.5	9.8	20.6	30.4	25.5	0.1941	0.0956

*: average radius of convergence-divergence draft tube

was measured by a flow meter before entering the reactor. The physical properties of resin particles are shown in Tab. 2. In order to simulate the rheological behavior of non-Newtonian viscous fluids, an aqueous solution of polymer carboxyl methyl cellulose was used, and its apparent viscosity is expressed as¹⁾

$$\mu_{app} = \frac{\tau}{\dot{\gamma}} = K \cdot \dot{\gamma}^{n-1} \quad (1)$$

Table 2. Physical properties of resin particle.

Diameter (mm)	Average diameter (mm)	Density ($\text{kg} \cdot \text{m}^{-3}$)	Apparent density ($\text{kg} \cdot \text{m}^{-3}$)
0.3–1.2	0.6	1.23–1.28	0.75–0.85

Since the shear rate of the fluid in the reactor is unmeasurable, it is considered that the shear rate, $\dot{\gamma}$, is only related with the air supply velocity for the internal circulation reactor with certain structural conditions. The relationship proposed by Kawase and Moo-Young [12] was adopted here:

$$\dot{\gamma} = 5000U_{Gr}, \text{ when } U_{Gr} > 0.4\text{m/s}$$

$$\dot{\gamma} = 1500U_{Gr}, \text{ when } U_{Gr} > 0.4\text{m/s}$$

The consistency index, K, and the flow index, n, of CMC solutions were obtained using a viscometer. The power-law parameters are given in Tab. 3. The surface tension of the different viscosity solutions was measured using a torsion balance. Surface tension data and densities for all the viscosities investigated are presented in Tab. 4.

Table 3. Rheological properties of CMC solutions.

CMC (wt. %)	$K, \text{Pa} \cdot \text{s}^n$	n
1.0 %	0.280	0.617
1.5 %	0.912	0.588
2.0 %	1.300	0.546

1) List of symbols at the end of the paper.

Table 4. Surface tension data and densities of CMC solutions.

CMC (wt. %)	$\sigma \times 10^3, N \cdot m^{-1}$	$\rho, kg \cdot m^{-3}$
1.0 %	66.0	1001.0
1.5 %	65.8	1001.6
2.0 %	65.3	1002.0

2.3 Experimental Procedure

During the experiment, a certain quantity of water or CMC solution was injected into the reactor. The air was introduced through a circular perforated plate sparger. Oil-free air from a compressor was employed as working gas for the system and nitrogen was used to purge. Either gas was introduced through a perforated plate sparger, which formed an up-flow with the liquid. Parts of the mixed air and liquid were brought into the circle interval between the draft tube and reactor wall, resulting in an internal loop flow. The subsequent measurements were employed after the circulation was stabilized. All experiments were performed at room temperature and no significant temperature variations occurred during the tests.

2.4 Measured Items

2.4.1 Gas Hold-Up

The method to evaluate the overall gas hold-up was the measurement of liquid global height corresponding respectively to aerated and non-aerated conditions. The gas hold-up in the downcomer and separator was measured between two pressure tapings 0.8 m and 0.4 m apart using an U-tube manometer, respectively. One kind of organic solvent in the U-tube manometer was used as a trace indicator. The gas hold-up in the riser was obtained from the material balance relation (2).

$$\varepsilon_r = \frac{V_F \varepsilon - V_d \varepsilon_d - V_S \varepsilon_S}{V_r} \quad (2)$$

2.4.2 Liquid Circulation Velocity

The liquid circulation velocity was measured with a conductimetric method. A tracer is injected at the bottom of the riser and its concentration is checked at two levels of the reactor. Knowing the distance between these two levels and the time lag between the two tracer signals, the liquid circulation velocity is calculated. The following equations can be obtained.

$$U_{Lr} = \frac{h_r}{T_C} \left(1 - \varepsilon_r + \frac{A_d(1-\varepsilon_d)}{A_r} \right) \quad (3)$$

$$U_{Ld} = \frac{h_r}{T_C} \left(1 - \varepsilon_d + \frac{A_r(1-\varepsilon_r)}{A_d} \right) \quad (4)$$

2.4.3 VMTCO

In this investigation the dynamic technique [13] was employed for the determination of the volumetric mass transfer coefficient of oxygen. For the mass-transfer determinations, the reactor was purged with nitrogen until the level of oxygen dropped to 0.5 mg/L before the air could be introduced into the reactor. The variation of DO concentration was monitored by OM-1 oxygen probe (the response time of oxygen probe is 0.1 s). Adjusted the air velocity to the set value, and recorded DO value in various time periods. The material balance equation on the oxygen with the assumption of perfectly mixed reactor is as follows:

$$C_L = \left(-\frac{1}{K_L a} \right) \left(\frac{dC_L}{dt} \right) + C^* \quad (5)$$

By integrating the Eq. (4), the volumetric mass transfer coefficient can be derived:

$$\ln \left(\frac{(C^* - C_L)}{(C^* - C_{L0})} \right) = K_L a t \quad (6)$$

In this work, all $K_L a$ values have been corrected to a common temperature of 20 °C using Howe's correlation [14]:

$$K_L a(20) = K_L a(T) \times 1.0125^{T-20} \quad (7)$$

3 Results and Discussion

The effects of physical parameters such as superficial gas flow rate, solid loading and liquid viscosity on ε_r , U_{Lr} , U_{Ld} and $K_L a$ determination were investigated in the airlift reactor for two- and three-phase systems.

3.1 Gas Hold-up

Effects of superficial gas flow rates on gas holdups in two-phase non-Newtonian systems are shown in Fig. 3. As seen from Fig. 3, the gas holdup increases with the superficial gas flow rate under different CMC solution concentrations, and variation of structural parameters of draft tubes has little effect on the gas holdup. At the same superficial gas flow rate, the gas holdup decreases by 1~5% with CMC solution concentrations. As the viscosity of the solution was increased, the turbulence in the riser subsided and the bubble size distribution increased. Large bubbles were present in the riser

along with small bubbles. For the more viscous CMC solutions bubble clusters (spherical-cap bubbles with a tail of small round bubbles) were observed to creep upward along the downcomer wall. The residence time of bigger bubbles is very short, since they rise rapidly through the riser, hence leading to lower the gas holdup in the CMC solutions compared to that in water. Comparison of the gas holdup between a conventional draft tube and a convergence-divergence draft tube shows that gas holdup in the convergence-divergence draft tube is much higher than that one in the conventional draft tube. It seems that convergence-divergence draft tube has a strong influence on the distribution and size of bubbles.

Figure 3. Effect of superficial gas flow rate on gas holdup in the riser with different CMC concentrations; ■ CMC 0 %, ● CMC 1.0 %, ▲ CMC 1.5 %, ▼ CMC 2.0 %.

3.2 Liquid Circulation

Effects of the superficial gas flow rate on the liquid circulation velocity for a three-phase system are shown in Fig. 4 and Fig. 5, respectively. As seen from Fig. 4, the liquid circulation velocity in the riser decreases with the superficial gas flow rate under different solids loading. At the same superficial gas flow rate, the liquid circulation velocity decreases obviously with solids loading. Comparison between conventional draft tubes and convergence-divergence draft tubes, the liquid circulation flow rate in the convergence-divergence draft tube is lower than that one in the conven-

Figure 4. Effect of superficial gas flow rate on liquid circulation velocity in the riser with different solids loading; ■ solid loading 0 %, ● solid loading 3 %, ▲ solid loading 6 %, ▼ solid loading 9 %.

tional draft tube. As seen from Fig. 5, the liquid circulation velocity in the downcomer exhibits the same rule as that one in the riser.

3.3 VMTCO in the Two-Phase System

3.3.1 Air/Water System

The effect of the superficial gas flow rate on the K_{La} of a reactor with convergence-divergence draft tube or tradition draft tube is shown in Figure 6. It could be seen that K_{La} increases with the increase of superficial gas flow rate within the experimental range. On the various air supply conditions, the draft tubes with various structural parameters enhance the mass transfer capacity compared with the traditional one. For No. 2 draft tube, the mass transfer coefficient is 20 % higher than that of No. 1 draft tube (conventional draft tube). For No. 3 draft tube, the mass transfer coefficient is 10 % higher than that of No. 1 draft tube. For No. 4 draft tube, the mass transfer coefficient is 30 % higher than that of No. 1 draft tube. That is to say, under different convergence-divergence conditions, the capacity to enhance mass transfer for convergence-divergence draft tubes is different. It may be

Figure 5. Effect of superficial gas flow rate on liquid circulation velocity in the downcomer with different solids loading; ■ solid loading 0 %, ● solid loading 3 %, ▲ solid loading 6 %, ▼ solid loading 9 %.

Figure 6. Effect of superficial gas flow rate on volumetric mass transfer coefficient of oxygen under air-water system; ■ No. 1 draft tube, ● No. 2 draft tube, ▲ No. 3 draft tube, ▼ No. 4 draft tube.

mainly caused by the ratio between L_c and L_d of convergence-divergence draft tubes. The capacity to enhance mass transfer for convergence-divergence draft tubes decreases with L_c/L_d within experimental range. We are studying on the optimum ratio between L_c and L_d .

Figure 7. Effect of superficial gas flow rate on volumetric mass transfer coefficient of oxygen with different CMC concentration; ■ CMC 0 %, ● CMC 1.0 %, ▲ CMC 1.5 %, ▼ CMC 2.0 %.

3.3.2 Air/CMC Solution System

Fig. 7 shows the effect of the CMC concentration in CMC solutions and the superficial gas flow rate on the K_{La} of the reactor with different draft tubes. It is also shown that K_{La} increases with increasing superficial gas flow rate within the experimental range, however, decreases significantly with increasing CMC solution concentration. K_{La} in 0 % CMC solution concentration is the highest. K_{La} in 1.0 % CMC solution concentration is much higher than that in 1.5 % CMC solution concentration. K_{La} in 1.5 % CMC solution concentration is higher than that in 2.0 % CMC solution concentration. K_{La} decreases quickly with the CMC solution concentration. With the same CMC solution concentration and superficial gas flow rate, the draft tubes with various structural parameters increase the mass transfer capacity compared with the traditional ones. The capacity to enhance mass transfer for different convergence-divergence draft tubes is different. While No. 4 draft tube has the greatest capacity to enhance mass transfer, No. 2 and No. 3 have greater capacity to enhance mass transfer, exhibiting the same rule as that of the air/water system. It may be also mainly caused by the ratio between L_c and L_d of convergence-divergence draft tubes.

3.4 VMTCO in the Three-Phase System

Fig. 8 shows the effect of the ratio of solids loading and superficial gas flow rate on the $K_L a$ of the reactor with different draft tubes. It is shown that the $K_L a$ increases with the increase of the superficial gas flow rate and the solids loading. Furthermore, increasing the solids loading and superficial gas flow rate, the draft tubes with various structural parameters all increase the mass transfer capacity compared with the traditional one within the experimental range. $K_L a$ in a reactor with different draft tubes under 0 % solid loading is much smaller than that in a reactor with different draft tubes under 3 % solid loading. $K_L a$ in a reactor with different draft tubes under 3 % solid loading is smaller than that in a reactor with different draft tubes under 6 % solid loading. $K_L a$ in a reactor with different draft tubes under 9 % solid loading is the biggest. It seems that solids can enhance the mass transfer to some extent within the experimental range.

Figure 8. Effect of superficial gas flow rate on volumetric mass transfer coefficient of oxygen with different solids loading: ■ solid loading 0 %, ● solid loading 3 %, ▲ solid loading 6 %, ▼ solid loading 9 %.

3.5 Correlation of VMTCO

Establish the correlation equation of the volumetric mass transfer coefficient of oxygen with the operating conditions,

liquid properties, and various structural parameters of draft tubes by linear regression on the experimental data, and calculate the average relative deviation and the maximum relative deviation between calculation and experimental results within the experimental range.

$$(Sh)_T = 0.156 \left(\frac{L_c}{L_d} \right)^{-7.731} \cdot \left(\frac{r_c}{r_d} \right)^{-0.053} \cdot Sc^{\frac{1}{2}} \cdot Re^{\frac{n+2}{2(n+1)}} \cdot Fr^{\frac{1n-4}{39(n+1)}} \cdot Bo^{\frac{3}{5}} \cdot \left(\frac{\mu_L}{\mu_G} \right)^{\frac{1}{4}} \cdot Sr^{\frac{4n+9}{10(n+1)}} \cdot \left(1 + \frac{\epsilon_s \rho_s}{(1-\epsilon_G - \epsilon_s) \rho_L} \right)^{1/3} \cdot \left(\frac{U_{sg}}{\sqrt{gh}} \right)^{0.25} \cdot \left(\frac{(1-\delta_s)^2}{(1-0.75\delta_s^{1/3})(1-2.15\delta_s)} \right)^{-0.508} \quad (8)$$

where $0 < \epsilon_s < 0.09$, $0.493 < \frac{L_c}{L_d} < 2.043$,

$0.678 < \frac{r_c}{r_d} < 1.000$

A comparison between experimental data and calculated values was made for both two- and three-phase system and good agreement obtained. Fig. 9 shows the comparison between experimental data and calculated values.

Figure 9. Comparison between calculated volumetric mass transfer coefficient of oxygen and experimental volumetric mass transfer coefficient of oxygen.

4 Conclusion

Hydrodynamics and mass transfer experiments have been carried out in internal loop airlift reactors with three different convergence-divergence draft tubes and one conventional draft tube. Under the two-phase and three-phase systems investigated, the volumetric mass transfer coefficient of oxygen in the reactor increases with the superficial gas flow rate. The convergence-divergence type draft tubes of three different structural parameters exhibit at least a 10 % higher

mass transfer coefficient than the conventional one. For the air/water two-phase system, with the CMC concentration of 0 %, 1.0 %, 1.5 % and 2.0 %, respectively, the VMTCO decreases with the increase of bulk viscosity. For the air/water/resin particle system, with solid loading of 0 %, 3 %, 6 % and 9 %, respectively, increasing the solid loading, increases the VMTCO. The correlation of the volumetric mass transfer coefficient with the operating conditions, liquid properties and structural parameters is established.

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Symbols used

a	$[m^{-1}]$	mean gas-liquid interfacial area per unit volume
A	$[m^2]$	cross-sectional area
Bo	$[-]$	Bond number, $(= gD_r^2 \rho / \sigma)$
D_r	$[m]$	diameter in the riser
F_r	$[-]$	Fraud number, $(= U_{Gr}^2 / g \cdot D_r)$
g	$[ms^{-2}]$	gravitational acceleration
K_L	$[ms^{-1}]$	liquid side mass transfer coefficient
n	$[-]$	rheological index
Q	$[m^3h^{-1}]$	superficial gas flow rate
Re	$[-]$	Reynolds number, $(= U_{Gr} \cdot D_r \cdot \rho / \mu)$
Sc	$[-]$	Schmidt number, $(= \mu / \rho \cdot \xi)$
Sr	$[-]$	area number, $(= A_r / (A_r + A_d))$
Sh	$[-]$	Sherwood number, $(= K_L \cdot a \cdot D_r^2 \xi)$
t	$[s]$	surface renew time
U_{Gr}	$[ms^{-1}]$	superficial gas velocity in the riser
U_{Ld}	$[ms^{-1}]$	superficial gas velocity in the downcomer
U_{Lr}	$[ms^{-1}]$	superficial liquid velocity in the riser
V_F	$[m^3]$	volume of the reactor

Greek symbols

$\dot{\gamma}$	$[ms^{-1}]$	shear velocity
δ_s	$[-]$	volume fraction, $(= V_s / (V_s + V_L))$

ε	$[-]$	gas holdup
ε	$[-]$	solid loading
ρ	$[kgm^{-3}]$	density
δ	$[kgs^{-2}]$	surface tension
ξ	$[-]$	liquid diffusion coefficient
μ	$[kgm^{-1}s]$	viscosity
μ_{app}	$[Nm^{-2}s^{-1}]$	apparent viscosity
τ	$[Nm^{-2}]$	shear force

Subscripts

d	refer to downcomer
G	refer to gas
L	refer to liquid
r	refer to riser
S	refer to separator
s	refer to solid

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