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# Gas holdup, bubble behavior and mass transfer in a 5 m high internal-loop airlift reactor with non-Newtonian fluid

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ABSTRACT

Gas holdup, bubble behavior, interfacial area and gas–liquid mass transfer in a 5 m internal-loop airlift reactor with non-Newtonian fluid were studied in the superficial gas velocity ($U_g$) range of 2–12 cm/s. Air and aqueous CMC solutions of 0–0.45 wt% were used as the gas and liquid phases, respectively. It was found that increased $U_g$ or CMC concentration led to a wider bubble size distribution and an increase in the bubble Sauter diameter. The volumetric mass transfer coefficient increased with an increase in $U_g$ and a decrease in CMC concentration. In the air–water system, $k_la/\alpha_g$ was found to be independent of $U_g$ and was 0.2 1/s, and a constant liquid-side mass transfer coefficient ($k_l$) was found in the heterogeneous regime. However, in the air–CMC solution system, the influences of the superficial gas velocity and liquid viscosity were much more complicated: $k_la/\alpha_g$ was not constant and was affected by the superficial gas velocity and CMC concentrations; the interfacial area increased with an increase in $U_g$ and a decrease in CMC concentration; $k_l$ increased more significantly with increasing $U_g$, and no obvious trend was found for the influence of CMC concentration on $k_l$.



## 1. Introduction

Airlift reactors are widely used in chemical and biochemical industrial processes, because of their simple construction, good heat transfer, low shear rate, low power input and easy scale up [1,2]. Mass transfer is one of the most significant factors in process design and reactor scale up, and has been intensively studied in airlift reactors during the past decades [3–9]. However, most of these studies have focused on experimental determination of the volumetric mass transfer coefficient ($k_la$), which is a global parameter that depends on reactor geometry, operating conditions and phase properties [7,10–14]. The common approach to describe $k_la$ is to correlate it with the factors that affect it. The separation of liquid-side mass transfer coefficient ($k_l$) and interfacial area ($a$) can allow the identification of whether $k_l$ or $a$ controlled the mass transfer rate. However, only a few investigations focus on such improvement [9,15–18]. In this work, we performed this study on the influence of non-Newtonian fluid.

In fact, the mass transfer rate in an airlift reactor depends on gas holdup, flow regime, bubble size distribution, bubble breakup and coalescence, interfacial area and liquid-side mass transfer coefficient [19]. Further, local measurements of these parameters are needed because they can provide much more details than global measurements [1,20,21], and can be used for validations of computational fluid dynamics (CFD) simulations [22].

The reactor size has a significant influence on the hydrodynamics and mass transfer rate [14,23–25]. It is commonly accepted that the hydrodynamics becomes independent of the column size only when the column diameter ($D$), column height ($H$), and aspect ratio ($H/D$) are larger than certain threshold values [2]. Wilkinson et al. [26] suggested that $H$ should be larger than 1–3 m. However, most works on the airlift reactor in the literature have used reactors of about 2 m [10,13,27,28], and only some works have used a reactor of 4 m high [5,6,29,30]. Therefore, an investigation using a larger airlift reactor will be valuable for a better understanding of the scale up behavior. In addition, most works on airlift reactor in the literature has been carried out with Newtonian fluid and much limited attention has been paid on studies of non-Newtonian or high viscosity liquid systems [15,27,31–34], despite the fact that in many chemical reactors the fluids have a relatively high viscosity or exhibit non-Newtonian behavior [35]. Different from that of Newtonian fluid, the viscosity of non-Newtonian fluid is dependent of shear rate. For instance, the viscosity of the shear thinning non-Newtionian fluids decreases when shear rate increases [36]. Further, the results in the literature are still not enough for a better understanding on the influence of non-Newtonian fluid. For example, Li et al. [32] studied the influence of non-Newtonian fluid on the hydrodynamics and mass transfer using a wide range CMC concentration of 1–4% in a 3.9 m high internal airlift reactor. However, this work was limited to experimental determination of $k_la$

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**Nomenclature**

*Notations*

| | |
|---|---|
| $a_l$ | gas–liquid interfacial area per unit liquid volume, $m^{-1}$ |
| $a_{large}$ | gas–liquid interfacial area of large bubble, $m^{-1}$ |
| $a_{small}$ | gas–liquid interfacial area of small bubble, $m^{-1}$ |
| $a$ | gas–liquid interfacial area per unit dispersion volume, $m^{-1}$ |
| $A_d$ | cross-sectional area of the downcomer, $m^2$ |
| $A_r$ | cross-sectional area of the annular riser, $m^2$ |
| $C_l$ | oxygen concentration in the liquid, $kg/m^3$ |
| $C_l^*$ | saturation oxygen concentration in the liquid, $kg/m^3$ |
| $C_{sensor}$ | liquid phase oxygen concentration given by sensor, $kg/m^3$ |
| $d_b$ | bubble diameter, m |
| $d_S$ | bubble Sauter diameter, m |
| $h$ | height, m |
| $K$ | consistency index, Pa $s^n$ |
| $k_l$ | liquid-side mass transfer coefficient, m/s |
| $k_{large}$ | liquid-side mass transfer coefficient of large bubble, m/s |
| $k_{small}$ | liquid-side mass transfer coefficient of small bubble, m/s |
| $k_{sensor}$ | sensor time constant, $s^{-1}$ |
| $k_l a$ | volumetric mass transfer coefficient based on dispersion volume, $s^{-1}$ |
| $k_l a_l$ | volumetric mass transfer coefficient based on liquid volume, $s^{-1}$ |
| $n$ | flow index, arbitrary units |
| $P$ | pressure, Pa |
| $t$ | time, s |
| $U_g$ | superficial gas velocity, cm/s |
| $U_{gr}$ | superficial gas velocity in the riser, cm/s |

*Greek symbols*

| | |
|---|---|
| $\alpha_g$ | gas holdup, arbitrary units |
| $\alpha_{gd}$ | gas holdup in the downcomer, arbitrary units |
| $\alpha_{gr}$ | gas holdup in the riser, arbitrary units |
| $\gamma$ | shear rate, $s^{-1}$ |
| $\mu_{app}$ | apparent viscosity, Pa s |
| $\tau$ | shear force, $N/m^2$ |
| $\rho_l$ | liquid density, $kg/m^3$ |

*Subscripts*

| | |
|---|---|
| d | downcomer |
| g | gas phase |
| l | liquid phase |
| r | riser |

and the reactor used a single-hole sparger, which was not usually adopted in industrial reactors. Therefore, the investigation on the influence of non-Newtonian fluid is needed, especially in a large airlift reactor.

This work studied the gas holdup, bubble behavior and gas–liquid mass transfer rate in a 5 m high internal-loop airlift reactor with water and aqueous solution of carboxyl methyl cellulose (CMC). The influences of the CMC concentration and superficial gas velocity ($U_g$) on the global and local gas holdup, bubble size distribution, volumetric mass transfer coefficient, interfacial area and liquid-side mass transfer coefficient were investigated.

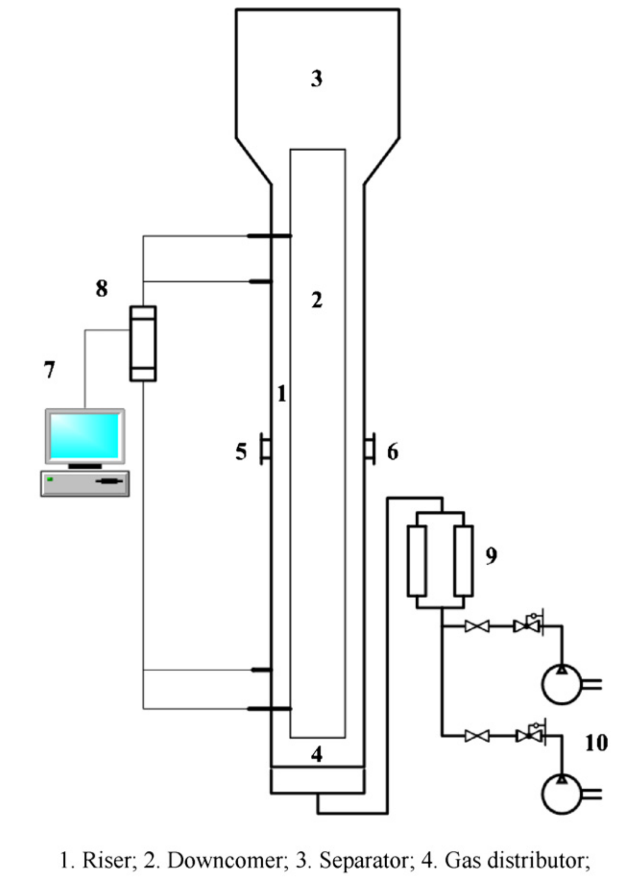


**Fig. 1.** Schematic of the experimental set-up.

## 2. Experimental

### 2.1. Experimental apparatus

The schematic of the experimental apparatus is shown in Fig. 1. The internal-loop airlift reactor used was made of Plexiglas. It comprised four main parts: annular riser, downcomer, gas–liquid separator and gas distributor. The total height of the reactor was 5 m. The riser was 0.28 m inner diameter (i.d.), and 4.1 m high. The separator was 0.48 m i.d., and 0.9 m high. The draft tube was 0.19 m outer diameter, 0.18 m i.d., and 4.0 m high. The gas distributor was an annular perforated plate with 196 holes of 1 mm diameter, thus the gas was only injected into the annular riser.

### 2.2. Physical properties

Air was used as the gas phase. Tap water and aqueous CMC solution of 0.2–0.45 wt% were used as the liquid phase. The apparent viscosity of the CMC solutions was measured by a viscometer, and can be expressed as [37]:

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

where $K$ is the consistency index, and $n$ is the flow index. The measured values of $K$ and $n$ are listed in Table 1. To illustrate the characteristic viscosity of the liquid phase, the apparent viscosities at the shear rate of 200 $s^{-1}$ are also listed in Table 1.