Gas holdup and mass transfer characteristics of carboxymethyl cellulose solutions in a bubble column with a radial gas sparger

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Abstract. The gas phase holdup and mass transfer characteristics of carboxymethyl cellulose (CMC) solutions in a bubble column having a radial gas sparger have been determined and a new flow regime map has been proposed. The gas holdup increases with gas velocity in the bubbly flow regime, decreases in the churn-turbulent flow regime, and increases again in the slug flow regime. The volumetric mass transfer coefficient \( k_L a \) significantly decreases with increasing liquid viscosity. The gas holdup and \( k_L a \) values in the present bubble column of CMC solutions are found to be much higher than those in bubble columns or external-loop airlift columns with a plate-type sparger. The obtained gas phase holdup \( \varepsilon_g \) and \( k_L a \) data have been correlated with pertinent dimensionless groups in both the bubbly and the churn-turbulent flow regimes.

List of symbols

\[ \begin{align*}
\alpha & \quad \text{m}^{-1} \quad \text{specific gas-liquid interfacial area per total volume} \\
A_d & \quad \text{m}^2 \quad \text{cross-sectional area of downcomer} \\
A_r & \quad \text{m}^2 \quad \text{cross-sectional area of riser} \\
d_b & \quad \text{m} \quad \text{individual bubble diameter} \\
d_{sa} & \quad \text{m} \quad \text{Sauter mean bubble diameter} \\
D_c & \quad \text{m} \quad \text{column diameter} \\
D_L & \quad \text{m}^2/\text{s} \quad \text{oxygen diffusivity in the liquid} \\
Fr & \quad - \quad \text{Froude number, } \left( \frac{U_g}{(g D_c)^{1/2}} \right) \\
g & \quad \text{m}^2/\text{s}^2 \quad \text{gravitational acceleration} \\
G_a & \quad - \quad \text{Galileo number, } \left( \frac{g D_c^3}{\mu_{\text{app}}} \right)^2 \\
H_a & \quad \text{m} \quad \text{aerated liquid height} \\
H_c & \quad \text{m} \quad \text{unaerated liquid height} \\
K_o & \quad \text{Pa} \cdot \text{s} \quad \text{fluid consistency index} \\
k_L a & \quad \text{s}^{-1} \quad \text{volumetric mass transfer coefficient} \\
n & \quad - \quad \text{flow behavior index} \\
N_i & \quad - \quad \text{number of bubbles having diameter } d_b \\
Sc & \quad - \quad \text{Schmidt number, } \left( \frac{\mu_{\text{app}}}{\rho \nu} \right) \\
Sh & \quad - \quad \text{Sherwood number, } \left( k_L a D_c/D_L \right) \\
U_g & \quad \text{m/s} \quad \text{superficial gas velocity} \\
U_{pr} & \quad \text{m/s} \quad \text{superficial riser gas velocity} \\
V_a & \quad \text{m}^3 \quad \text{aerated liquid volume} \\
V_c & \quad \text{m}^3 \quad \text{unaerated liquid volume} \\
\sigma & \quad \text{N/m} \quad \text{surface tension of the liquid phase} \\
\varepsilon_g & \quad - \quad \text{gas holdup} \\
\mu_{\text{app}} & \quad \text{Pa} \cdot \text{s} \quad \text{effective viscosity of non-Newtonian liquid} \\
\rho & \quad \text{kg/m}^3 \quad \text{liquid density} \\
\dot{\gamma} & \quad \text{s}^{-1} \quad \text{shear rate} \\
\tau & \quad \text{Pa} \quad \text{shear stress}
\end{align*} \]

1 Introduction

Bubble column reactors are widely used in the fields of petrochemical, biotechnological and various chemical processes. In comparison to other multiphase reactors bubble columns have the advantage of simplicity, low operating costs and high heat and mass transfer rates between the phases. Various types of bubble column reactor have been tested and modified in many ways to suit particular applications to improve their performance [1-6]. There are external- and internal-loop airlift reactors [7-10], airlift reactors with a net draught tube [11], bubble columns with a horizontal gas sparger [12], and down flow bubble columns.

Bubble column reactors would be a suitable choice for the fermentation of shear-sensitive cells such as mycelial fungi, animal, and plant cell cultures since they provide a relatively gentle and uniform mixing. Mycelial fermentation broths tend to have a highly non-Newtonian fluid behavior. Non-Newtonian fluid behavior of fermentation broths has very significant effects on the hydrodynamics and the performance of bioreactors. The rheological behavior of aqueous polymer solutions such as CMC, carboxy-polymethylene, and polyacrylamine (PAA) is similar to that of mycelial fermentation broths. These solutions can therefore be used to simulate the rheological behavior of fermentation broths containing filamentous microorganisms. With these polymer solutions and mycelial fermentation broths, several research groups studied the influence of non-Newtonian flow behavior on the performance of bubble columns with various gas sparger types (single orifice, perforated plate, sintered plate, rubber plate, and ring sparger) and presented correlations to predict the gas phase holdup \( \varepsilon_g \), volumetric mass transfer coefficient \( k_L a \), and specific interfacial area \( a \).

Deckwer et al. [2] measured \( k_L a \) values in a bubble column with different gas spargers (sintered plate, rubber plate, and perforated plate) and reported that \( k_L a \) was strongly dependent on the type of gas sparger at lower \( U_g \) in the bubbly and churn-turbulent flow regimes, but slightly affected by the gas sparger type in the slug flow regime.
To enhance the gas phase holdup and mass transfer rate, a radial gas sparger was employed in the present study. It can be easily replaced by one having a different surface area regardless of the column size. At a given column diameter and gassing rate, the sparger area can be varied with a proper selection of the sparger height and diameter.

In the present study, \( \varepsilon_g \) and \( k_La \) in a bubble column with the radial gas sparger have been determined for different concentrations of CMC solutions and the obtained data have been correlated with the pertinent dimensionless groups. Also, a flow regime map has been constructed.

2 Experimental

2.1 Experimental equipment and conditions

Experiments were carried out in a 0.115 m-ID x 2.0 m-H Plexiglas column with a radial gas sparger as shown in Fig. 1. The radial gas sparger was made of sintered stainless steel cylinder (0.038 m-OD x 0.15 m-H; 5 \( \mu \)m-mean pore size; Pall Ultrafine Filtration Co.). Initially, the unaerated liquid height was maintained at 0.9 m so that the ratio of unaerated liquid height to column diameter \( (H_{\text{aq}}/D_c) \) was about 8. Oil-free compressed air was fed into the column through a calibrated flow meter and the gas sparger and the superficial air velocity \( U_{sg} \) ranged from 0.009 to 0.098 m/s.

An oxygen electrode was installed at the center of column at 0.8 m above the base of column. A polarographic electrode (YSI 5739) was used to measure dissolved oxygen concentration. The response time of the oxygen probe (the time required to attain 63% of a step change) was less than 6 seconds at 25 °C. Bubble size was measured by means of a photographic technique [13] which has been widely used because of its simplicity. But, it gives reliable results only in the homogeneous or bubbly flow regime. The bubbles in the vicinity of the transparent bubble column wall were photographed by a still camera and the bubble size was measured by using an optical comparator. Bubble size distributions were analyzed only in the bubbly flow regime with 0.7 wt% CMC solution.

2.2 Data analysis

The gas phase holdup was measured by using the volume expansion method which was chosen of its simplicity and reliability in comparison with the differential pressure profile method. The gas phase holdup \( \varepsilon_g \) was determined from the following relationship:

\[
\varepsilon_g = \frac{V_{\text{aq}} - V_c}{V_c}
\]

where \( V_{\text{aq}} \) and \( V_c \) are the unaerated and aerated liquid volumes, respectively.

Fig. 1. Experimental apparatus. A. bubble column, B. radial gas sparger, C. supporter, D. DO electrode, E. DO meter, F. data acquisition system, G. gas flow meter

The dynamic oxygen adsorption or desorption method [14] was used to determine \( k_La \) values. The specific interfacial area is related to the gas phase holdup \( \varepsilon_g \) and the volume-to-surface mean bubble diameter \( d_{vs} \) as:

\[
a = \frac{\varepsilon_g}{d_{vs}}
\]

Since the bubble size is not uniform, their size distribution should be taken into account. The volume-to-surface mean or Sauter mean bubble diameter in Eq. (2) is represented by:

\[
d_{vs} = \frac{\sum N_i d_{bi}^3}{\sum N_i d_{bi}^2}
\]

where \( N_i \) is the number of bubbles with diameter of \( d_{bi} \).

2.3 Determination of liquid-phase properties

Since CMC solutions are known to have a pseudoplastic flow behavior with a power law relationship between shear rate \( \dot{\gamma} \) and shear stress \( \tau \), the apparent viscosity can be determined from the following relationship:

\[
\mu_{\text{app}} = \frac{\tau}{\dot{\gamma}} = K \dot{\gamma}^{n-1}
\]

where \( K \) and \( n \) are respectively the fluid consistency index and the flow behavior index. The viscosity of CMC solutions (0.7 ~ 1.6 wt% in tap water) were measured by using a Brookfield viscometer (Model DV-II). Surface tension of CMC solutions was measured by using a surface tensiometer (Fisher surface tensiometer 2). The obtained viscosity and surface tension of different CMC solutions are given in Table 1.