Chemical Engineering Journal 149 (2009) 301–310

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Gas void ratio and bubble diameter inside a deep airlift reactor

J.P. Giovannettone [a], E. Tsai [b], J.S. Gulliver [c,*]

[a] Institute of Water Resources, Hydrologic Engineering Center, 609 2nd St. Davis, CA 95616, USA
[b] MWH, 300 N Lake Ave, Pasadena, CA 91101, USA
[c] Department of Civil Engineering, University of Minnesota, Minneapolis, MN 55455, USA

ARTICLE INFO

Article history:
Received 11 December 2007
Received in revised form 27 October 2008
Accepted 9 November 2008

Keywords:
Aeration
Bubble columns
Airlift reactor
Hydrodynamics
Voidage
Bubble size
Gas holdup

ABSTRACT

Void ratio (gas holdup) and bubble diameter measurements were made inside a 1.06-m diameter column containing bubbly flow at depths up to 24 m. Experiments were performed in order to identify differences in trends with column geometry and operating conditions from those found in smaller columns. Void ratio was found to increase as depth decreased regardless of the sparger type or column height. It was also found that larger columns exhibit a wider range of void ratios between the top and bottom than for smaller columns. A straightforward model was developed to predict the void ratio at heights greater than 2 m above the column bottom. The model incorporates the influences of hydrostatic pressure, superficial gas and liquid velocities, and a fitted bulk bubble-rise velocity while ignoring gas transfer with air as the gas of interest. The fitted slip velocities were found to compare well with literature measurements of single-bubble slip velocities. If the void ratio profiles are already known, the equation can also be used to estimate the bubble slip velocity, which is difficult to measure experimentally.

Bubble diameter measurements were made using a submersible camera attached to a trolley. It was found that the Sauter mean bubble diameter does not change with gas flow rate and depth and can decrease substantially when not taking the few largest bubbles (outliers) into account. In contrast, differences were observed when comparing column types. With or without the outliers removed, the bubble column contained larger bubbles than the airlift reactor, which may justify conversion to an airlift reactor and clarify some important factors in the operation of commercial-scale columns.

1. Introduction

Two-phase gas–liquid reactors in industry can be up to 40 m in height with diameters up to 10 m and can be in the form of either a bubble column or an airlift reactor. An airlift reactor is different from a bubble column in that it separates the rising and sinking fluid into two containers, the riser and downcomer, respectively. Both types of reactors are used in several applications, which include the catalytic conversion of hydrocarbons, coal liquefaction, or the synthesis of hydrocarbons from carbon monoxide and hydrogen, absorption processes, extraction, fermentation, among others. There is also interest in boiling gas–liquid flow, such as may occur in a nuclear reactor. Three types of gas–liquid flows may exist in these reactors depending on operating conditions [1]: (1) bubbly flow (up to 0.05–0.08 m/s), where individual bubbles rise with or against the flowing liquid; (2) slug flow, where a bullet shaped Taylor bubble rises at high velocity while shedding smaller bubbles; and (3) annular flow, where a liquid film moves along the wall and a gas core is present inside this film. One important application that operates exclusively in the bubbly flow regime is the use of an airlift reactor to replenish oxygen in the hypolimnion (bottom) of a lake or reservoir [2]. Reoxygenation helps promote the survival of aerobic bacteria, prevent algal blooms and odor problems, and improves living conditions for aquatic life. A typical setup [3] consists of a riser in the middle of the device, which removes the unaerated water from the hypolimnion, and an outer shell where the re-aerated water is returned to the hypolimnion.

The main parameters that characterize the hydrodynamics inside a bubble column are the gas void ratio, mean bubble diameter, mixing, and the volumetric mass transfer rate, while airlift reactors add the liquid circulation velocity. These can be affected by the geometry of the column and the existing operating conditions, of which the gas and liquid flow rates are the most important. Other variables to consider are the properties of the continuous media used inside the reactor and the type of sparger used to introduce gas into the media. The current study will investigate the effects of changing the geometry and operating conditions of a full-scale airlift reactor on the void ratio and mean bubble diameter, with comparisons made to a bubble column. Measurements of void ratio and bubble diameter allow calculations of the interfacial

* Corresponding author at: Department of Civil Engineering, Room 127A, University of Minnesota, Minneapolis, MN 55455, USA. Tel.: +1 612 625 4080; fax: +1 612 626 7750.
E-mail address: gulli003@umn.edu (J.S. Gulliver).

1385-8947/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.cej.2008.11.024

Nomenclature

a	specific surface area, m^{-1}
A	cross-sectional area, m^2
A_b	bubble surface area, m^2
C	concentration in liquid phase, kg m^{-3}
C_b	concentration in gas phase, atm
d	bubble diameter, m
D_c	column diameter, m
h	water height, m
H	Henry's Law constant, atm m^3 kg^{-1}
K_L	liquid film coefficient, m/s
L	pressure head, m
n	moles of gas in volume V_b
P	pressure, atm
R	universal gas constant, atm m^3 mol^{-1} K^{-1}
S	estimator of scale
T	absolute temperature, K
u	superficial velocity, m/s
U_s	bubble-rise velocity relative to u_l, m/s
v	velocity of bubbles relative to fixed coordinates, m/s
V_b	bubble volume, m^3
z	vertical coordinate or measurement height
z_s	z-score

Greek symbols

ρ_b	gas density, kg m^{-3}
φ	gas void ratio
σ	standard deviation of bubble size, m
$\sigma_{\ln}$	standard deviation of the natural log of bubble size

Subscripts

2	2″ pipe
a	mean
atm	local atmospheric
b	Sauter mean
d	downcomer
g	gas
Gas	during gas injection at current pressure tap
Gas-1	during gas injection at pressure tap below current tap
i	index
l	liquid
$Post$	after gas is shut off at current pressure tap
$Post$-1	after gas is shut off at pressure tap below current tap
Pre	before gas injection at current pressure tap
Pre-1	before gas injection at pressure tap below current tap
r	riser
s	free surface
Tap	current pressure tap
Tap-1	pressure tap below current tap

surface area of the bubbles, which are important to mass transfer calculations [4].

2. Previous work

A number of studies have been performed in an attempt to design airlift reactors and bubble columns to be more efficient at gas transfer. In order to accomplish this, an estimate of the gas transfer rate needs to be made. A higher gas transfer rate is characterized by a high total interfacial surface area of the bubbles, which requires estimates of void ratio and mean bubble diameter. An important issue is that previous studies have used relatively short columns with the tallest being 10.5 m [5], 7.23 m [6], and 6 m [7]. Results from these studies have shown that column height has a negligible effect on void ratio [8–11]; therefore, an overall void ratio has been calculated for the entire column [12–15]. In contrast, it was found in the present study that gas void ratio does increase with height, which indicates that caution must be taken when extrapolating the results from smaller columns to full-scale column heights.

Results concerning the superficial liquid velocity are more consistent. When varying the liquid circulation velocity from 0 m/s (bubble column) to a positive value (airlift reactor), void ratio has been found to decrease [7,12,15]. Due to the liquid circulation present in an airlift reactor, the down flowing regions near the wall are reduced, which allows bubbles to enter and leave quickly, reducing the void ratio.

A large portion of the volume of the smaller columns is taken up by the sparger zone, which is located above the sparger. The sparger zone is where bubble coalescence and breakup are not in equilibrium and, as a result, where bubble size changes more rapidly with height than throughout the remainder of the column. This will affect the measured bubble size in the smaller columns. Colella et al. [16] measured bubble diameter in two bubble columns of varying heights and diameters and found that bubble size decreased with height in the shorter bubble column, but did not change in the larger bubble column above a height of 0.375 m above the sparger. Polli et al. [17] found similar results and estimated the sparger zone to extend one column diameter above the sparger. In contrast, Ohkawa et al. [18] and Magaud et al. [19] found that bubble diameter changes little with height in columns of comparable size. One explanation for the different observations in the sparger zone is the initial size of the bubbles compared to the dynamic equilibrium of bubble size. If the initial size of the bubbles is smaller than the terminal bubble size, then the trend in bubble size will be increasing in the sparger zone, and vice versa. If the initial bubble size is near the equilibrium size, then a negligible change should be observed with height. The equilibrium size is determined by effects due to shear [20–23], but little work has been done concerning the amount of shear produced in a bubble column.

There are conflicting results in the literature on the effects of changing gas and liquid flow rates upon bubble size. Some studies have found that bubble diameter decreases with superficial gas velocity [24,25], which is due to increased bubble breakup at higher gas flow rates, creating a greater number of smaller bubbles. Miyahara and Hayashino [26] found that mean bubble size decreases with superficial gas velocity at lower velocities (0.003–0.008 m/s) and then increases to an equilibrium diameter at higher gas velocities. In contrast, an increase in superficial gas velocity has also been found to increase bubble diameter [17,19,27,28] or have no effect [7,18,29,30]. In terms of liquid velocity, Colella et al. [16] found that bubble columns ($u_l = 0$) and airlift reactors ($u_l > 0$) produce bubbles of similar sizes throughout the height of the columns.

Further information on the literature comparisons can be found in Giovannettone [31]. It is difficult to make generalizations from these studies due to the multiple variables being altered between experiments [16,17]. The columns used are shorter than most industrial reactors and do not come close to the depths that exist in applications involving lake and reservoir aeration, which leaves unanswered questions about scale-up. The purpose of the current work is to determine the effects of column geometry and specific operating conditions on void ratio and mean bubble diameter in a deep airlift reactor and bubble column (23.4 m) by changing only one parameter between experiments. This will decrease scale-up issues and allow more assertive conclusions to be made than in previous studies. Three column heights and three spargers will be tested. The results are compared to those from previous studies