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Gas holdup and mixing characteristics of a novel forced circulation loop reactor

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Abstract

Gas holdup and mixing time were characterized in a forced circulation internal loop draft-tube reactor (unaerated aspect ratio ≈ 6, downcomer-to-riser cross-sectional area ratio = 0.493) as functions of the forced liquid superficial velocity in the riser (U_{Lr}) and the gas superficial velocity in the riser (U_{Gr}). Data were obtained in air–water system. The operation ranges were $0 \leq U_{Lr} \leq 0.051$ m/s and $7.8 \times 10^{-3} \leq U_{Gr} \leq 3.9 \times 10^{-2}$ m/s for the liquid and gas velocities, respectively. Under forced flow conditions the reactor always operated in the bubble flow regimen, but operation as an airlift reactor (i.e. no forced flow of liquid) produced a heterogeneous churn-turbulent flow regimen. Forced flow of liquid enhanced gas holdup in comparison with the airlift mode of operation. Mixing time generally declined with increased flow rates of gas and liquid. The ability to maintain a bubble flow regimen through forced flow of liquid allowed the reactor to attain gas holdup values of >0.12 that are difficult to achieve in air–water in conventional bubble columns and airlift reactors.

Keywords: Gas holdup; Mixing time; Power consumption; Forced circulation loop reactor; Jet loop reactor; Airlift bioreactor

1. Introduction

Gas–liquid reactors are commonly used in industrial processes that involve absorption or desorption of a gas. Examples of such reactors include bioreactors that are used in aerobic microbial and cell culture processes. Two frequently used types of gas–liquid reactors are the bubble column and airlift loop reactor in which mixing is achieved solely through the action of the injected gas. Effective use of these reactors generally requires a homogenous bubble flow regimen of operation that is characterized by the presence of ellipsoidal bubbles of a relatively uniform size (typically ≤0.9 m in major diameter in air–water systems). Uniformly sized small bubbles have a relatively high specific interfacial area for gas–liquid mass transfer compared with larger spheroidal or spherical cap bubbles. The latter coexist with small bubbles once the flow regime changes to churn-turbulent or heterogeneous flow.

Flow regimen transition from bubble flow to churn-turbulent flow occurs at relatively low values of gas injection rates in bubble columns and airlift reactors. This flow transition has associated adverse outcomes, including poor contact of the gas and liquid phases, a broad residence time distribution of the gas phase and reduced efficiency in gas–liquid mass transfer. Reactor designs that can extend the bubble flow regimen of operation to higher values of gas flow rates than in bubble columns and airlift reactors, are potentially useful [1].

This work reports on characterization of gas holdup and liquid phase mixing in a forced circulation loop reactor with a novel type of gas sparger, for possible use as a gas–liquid contactor. The use of a novel sparger design in combination with forced circulation of the liquid through an external centrifugal pump, is shown to substantially extend the range of gas flow rates at which the desirable bubbly flow regime can be maintained in the reactor. Other designs of forced circulation loop reactors have been reported in the literature [2–4], but they did not use gas spargers that were specifically designed to control bubble size. Single orifice nozzles were generally used in the past for injecting the gas and this often lead to a heterogeneous flow regimen.

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Nomenclature

e_T	power input per unit volume (W/m^3)
g	gravitational acceleration (m/s^2)
ΔH	vertical distance between the pressures taps (m)
H_L	unaerated liquid height (m)
L_M	mixing tube length (m)
M	molar mass (kg/kmol)
ΔP_R	differential pressure between pressure taps in riser or downcomer (Pa)
ΔP_s	differential pressure between inlet and outlet of sparger (Pa)
P_t	pressure at top section (Pa)
Q_L	volumetric liquid flow rate (l/h)
Q_m	molar gas flow rate (kmol/s)
R	universal gas constant (J/kmol K)
T	temperature (K)
U_G	superficial gas velocity in bubble column (m/s)
U_{Gr}	superficial gas velocity in riser (m/s)
U_{Lr}	superficial liquid velocity in riser due to forced circulation (m/s)
v_{LN}	liquid velocity in nozzle (m/s)
v_o	gas velocity through the sparger hole (m/s)
V_L	liquid volume in the reactor (m^3)

Greek symbols

ε	gas holdup
ρ	density (kg/m^3)
Ω	efficiency factor

Subscripts

d	downcomer
D	dispersion
G, g	gas phase
L	liquid phase
r	riser
T	total

2. Materials and methods

2.1. Internal-loop reactor

Measurements were made in a novel design of an internal loop recirculation reactor (Fig. 1). The reactor consisted of a gas–liquid sparger zone (Fig. 1) connected to cylindrical vessel that had a concentric draft-tube downcomer zone. The gas–liquid sparger (Fig. 1) had separate inlets for gas and liquid. Just before the liquid entered the gas injection zone, it passed through a static mixer that produced a spinning or swirling motion of the liquid [5]. The gas was injected into swirling liquid though holes located at the periphery of the conical region of the sparger, as illustrated in Fig. 1. The swirling motion of the liquid past the gas injection point caused the bubbles to be detach and sweep away from the injection holes while they were still relatively small. The exact size of the bubbles at detachment depended on the rates of gas and liquid flow. Smaller bubbles were produced at relatively low values of gas flow rate in combination with high values of liquid flow rate. Air and water were used at the liquid and gas phases, respectively.

Table 1
Reactor geometry and operational parameters

Description	Value
Bioreactor diameter (m)	0.1484
Unaerated liquid height (m)	0.914
Liquid height above draft-tube (m)	0.032
Working volume (m^3)	0.01625
Downcomer-to-riser cross section area ratio (–)	0.493
Draft-tube length (m)	0.865
Inner diameter of draft-tube (m)	0.083
Static mixer	20 mm length, 45° inclination angle
Mixing tube length L_M (m)[a]	0.124, 0.236

[a] Data were obtained with the shorter tube, except for Fig. 8.

Geometric details of the reactor are shown in Table 1. The reactor was piped to the liquid circulation pump, as shown in Fig. 2. A heat exchanger placed in the circulation piping was used to control temperature. Air was supplied from a compressor through a pressure regulator, control valve, rotameter and buffer tank to facilitate precise control of flow rate. A differential pressure transmitter (Rosemount 3051, USA) was used to measure the pressure difference between the inlet and outlet of the sparger zone. The pressure measurement points are shown in Fig. 2. At any steady state, the differential pressure was sampled at 1 s intervals for 30 s and data were recorded using a computer. All experiments were carried out with air and water at 20.5 ± 1.0 °C.

2.2. Measurements

Overall gas holdup was measured using the volume expansion method [6]. Gas holdup values in the riser and downcomer zones were calculated from the differential pressure measurements in these zones, as follows:

$$\varepsilon = \frac{\Delta P_R}{(\rho_L - \rho_G) g \Delta H} \tag{1}$$

where ΔP_R is the pressure differential between measurement points in the riser or downcomer, ρ_L and ρ_G are densities of the gas and liquid phases, respectively, g is gravitational acceleration and ΔH is the vertical distance between the pressure taps in the relevant measurement zone. At every hydrodynamic steady state, 30 measurements of ΔP_R were used to calculate the average holdup.

The power delivered to the reactor was derived from the gas and liquid phases. The total specific energy input e_T was calculated [6–8] as follows:

$$e_T = \frac{Q_m RT}{V_L} \ln\left(1 + \frac{\rho_L g H_L}{P_t}\right) + \frac{\Omega}{2V_L} Q_m M v_o^2 + \frac{Q_L}{2V_L} \rho_L v_{LN}^2 + \frac{\Delta P_s Q_L}{V_L} \tag{2}$$