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Investigations of flow structure and liquid mixing in bubble column equipped with selected internals

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HIGHLIGHTS

- Multiple techniques used elucidated complex flow structure in bubble column equipped with internals.
- Alterations to mixing effects possible with suitable combinations of internals.
- Fast response heat flux probe proved useful tool to allow assessment of internals effects.

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ABSTRACT

Flow structures and liquid mixing effects are examined in a gas sparged column equipped with internals selected to achieve desired effects. The internals used in this study include a concentric tube bundle, a baffle designed to alter flow of bubbles across column cross-section and a multi-arm gas distributor with downward facing holes. The selection represents consideration of heat removal system, minimal obstruction to flow and desirable mixing effects. Measurements have been made in a 0.15 m ID column in two-phase air-water and three phase air-water-glass beads systems. The air flow rate is varied from 0.03 to 0.3 m/s to cover a wide range of velocities and the particles are 40 μm glass beads. Liquid phase mixing effects are examined with tracer injections from which mixing time and axial dispersion coefficients are obtained. For more detailed survey of flow structure neutrally buoyant particles are employed. Measurements with a fast response heat flux probe in two and three phase systems are compared and analyzed to demonstrate its potential use for screening of internals. Averaged flow structure in the presence of the internals is proposed from observations with different techniques.

1. Introduction

Gas agitated gas-liquid (g-l) and gas-liquid-solid (g-l-s) reactors are an attractive option compared to mechanically stirred tank reactors due to their simple construction, low operating costs and good heat and mass transfer rates (Li et al., 2003; Li and Prakash, 2002; Kluytmans et al., 2001;Deckwer and Schumpe, 1993). These advantages have provided wide application areas for these contactors in biochemical, chemical, petrochemicals and other industries (Jhawar and Prakash, 2012; Duduković et al., 2002; Prakash et al., 1999; Deckwer and Schumpe, 1993; Fan, 1989; Shah et al., 1982). In its basic form, the reactor is a hollow cylinder and gas is sparged through in the form of bubbles into a liquid or suspension of solid particles in liquid. Hydrodynamics and heat transfer characteristics of these hollow bubble columns have been investigated extensively in literature studies (Li and Prakash, 2001; Gandhi et al., 1999; Deckwer, 1992; Saxena et al., 1992; Ueyama et al., 1980; Hills, 1974). A limited number of literature studies have also investigated the effects of internals on bubble column hydrodynamics (Jhawar and Prakash, 2014; Youssef and Al-Dahhan, 2009; Larachi et al., 2006). These studies clearly point to alterations in flow pattern, mixing intensities and general hydrodynamics due to insertion of internals in a hollow bubble column. Changes to design configurations have been reported to clearly affect the hydrodynamic behavior of the bubble column which is expected to affect the rate of transport processes (Youssef and Al-Dahhan, 2009; Larachi et al., 2006).

In a previous study the authors presented some of the results obtained with internals in a solid-free bubble column and pointed to changes in flow patterns and potential effects on liquid phase mixing (Jhawar and Prakash, 2014). The changes in flow patterns were deduced with the help of a fast response heat transfer probe which could capture alterations to flow structure in the presence of different internals. However, mixing effects were not quantified and changes to flow structure were not elucidated in details. In this

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Nomenclature

A	heat transfer area (m^2)
C	tracer concentration
Da	coefficient of axial dispersion (m^2/s)
D_C	column diameter (m)
h	heat transfer coefficient ($kW/m^2\ °C$)
k	thermal conductivity (W/m K)
N	number of data points
q	heat flow rate (kW)
r	radial location (m)
R	radius of the column (m)
T	temperature (°C)
t	time (s)
V	superficial velocity (m/s)
z	axial location from the bottom of the column (m)
Δx	thickness of thermal barrier (m)

Subscripts

avg	average
b	bulk
c	center
E	end point
g	gas
i	instantaneous
l	liquid
Su	surface

study the effects of internals on liquid phase mixing parameters are determined with the help of tracers. Moreover, the complicating effects of internal design on local flow structure are observed in more details with the help of neutrally buoyant particles (NBPs). The results obtained with the tracers and NBPs are linked to data obtained with a heat transfer probe which can be used for a quick screening of internals. The main internal consists of a bundle of vertical tubes in a circular arrangement, and a secondary internal consisting of a fixed, six-blade baffles placed between the gas distributor and bottom of the tube bundle. The tube bundle represents a commonly used arrangement to provide heat transfer surface and may have similar effects as a draft tube on column hydrodynamics. The six-blade baffle design was selected to work as a bubble diffuser by dispersing the rising bubbles stream over the column cross-section. This arrangement was expected to avoid tunneling effect which can be created to bubbles flow in the presence of the concentric tubes internal. In the three-phase slurry system, measurements are made with the heat transfer probe only since other techniques became less reliable in this system. The measurements obtained with the heat transfer probe in two-phase and three phase bubble column are compared pointing out differences and similarities.

2. Experimental

Experiments were conducted in a Plexiglas column of 0.15 m internal diameter and height of 2.5 m (Fig. 1a). The column was supported by a rigid metallic structure to keep it vertical and to minimize mechanical vibrations that could potentially affect pressure and heat transfer signals. The gas was introduced to the column using a coarse sparger with four arms, each of which had seven downward facing holes for gas injection that were 1.9 mm in diameter. A concentric tube bundle consisting of fifteen tubes (9.5 mm in diameter and 1.5 m long) was placed 30 cm above the column bottom, as can be seen in Fig. 1a. Experiments were carried out with the tube bundle internal (CT) and a combination of the tube bundle and baffle internals (CTB). A top view of the concentric baffle internal is shown in Fig. 1b.

Additional design details of the internals can be found in Table 1. Oil free compressed air was the gas phase, tap water the liquid phase and 49 μm glass beads (Potters Industries, spheriglass® A glass) of density 2500 kg/m^3 constituted the solid phase. The gas flow rate was measured using calibrated sonic nozzles of different diameters (0.7 mm, 1.5 mm and 2.5 mm). The superficial gas velocity was varied from 0.03 to 0.3 m/s. The un-aerated liquid/slurry height in the column was maintained around 1.45 m. A measuring tape was provided on the column to note the liquid level and dispersion height. Solids concentration was maintained at 10 vol.%.

Liquid phase mixing was investigated using dye and salt tracers. The tracer solution was added to the top of the column using a ring-type sparger containing four, 1.3 mm diameter holes. The sparger was positioned 0.38 m from the top of the column, as seen in Fig. 1a. Further details on the design of the injection system can be found in George (2015). About 7.5 cc of the dye solution was injected into the working column within a 10 s time span. Videos of the system were recorded near the bottom of the column, near the distributor region. For clarity, a white background was placed behind the portion of the column under investigation. The time required for complete mixing was determined by noting the point when the color of the continuous phase seemed to be constant between consecutive frames. This was determined with the help of a video editing software (CyberlinkPowerDirector 12). The experiment was repeated at least three times for each internal and superficial gas velocity investigated. The mixing times presented in the results section are an average of the mixing times obtained from repeat runs. Experiments carried out with salt tracer solution required the use of a conductivity probe (Cole Parmer, Inlab 731 ISM probe) and multimeter (Cole Parmer, SevenExcellence Multiparameter meter). The probe was positioned 0.05 m from the bottom of the column and instantaneous salt conductivity was measured at 1 s intervals using the LabX direct pH software. As a precaution, all readings were taken after the meter reported stable temperature values. The time required for complete mixing was obtained by determining the point at which the column's conductivity first became constant from the onset of aqueous salt injection. This was obtained from a plot of instantaneous conductivity with time.

For visual observations of mixing patterns in the bubble column, near-neutrally buoyant particles were added to the working bubble column under various conditions. Video recordings were made with a camera suitable for tracking particle motion (Canon PowerShot SX50 HS) and observations were noted from frame-by-frame analysis of the recordings. Based on initial tests, black colored particles were selected to carry out these observations, since this color particles were easiest seen in the video recordings. The particle sizes selected were 4 mm and 9 mm, and their densities were within 5% of that of water. The 4 mm particle was selected because its diameter was smaller than the spaces between the tubes of the tube bundle internal, allowing for the investigation of flow between tubes. This small diameter was also expected to have minimal effects on local flow. As superficial gas velocity increased, tracking the 4 mm particle became difficult due to diminished visibility. After visibility tests with different size particles, a 9 mm particle was selected to ensure visibility at higher