CHEMICAL ENGINEERING RESEARCH AND DESIGN 109 (2016) 486–494

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Experimental studies of gas holdup in a slurry bubble column at high gas temperature of a helium–water–alumina system

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ARTICLE INFO

Article history:
Received 8 August 2015
Received in revised form 23 January 2016
Accepted 23 February 2016
Available online 2 March 2016

Keywords:
Slurry bubble columns
Hydrodynamic
Gas holdup
Helium gas
Solid concentration

ABSTRACT

In this paper, overall gas holdup is investigated experimentally for a helium gas at 90 °C injected through a slurry of water at 22 °C and alumina solid particles in a slurry bubble column reactor. This work examines the effects of superficial gas velocity, static liquid height, solid particles concentration and solid particle diameter, on the overall gas holdup of the SBCR. These effects are formulated in forms of empirical equations. From the experimental work, it is found that the overall gas holdup increases by increasing the superficial gas velocity with a higher rate of increase at lower superficial gas velocity. In addition, the overall gas holdup decreases by increasing the static liquid height and/or the solid concentration at any given superficial gas velocity. Moreover, at a higher solid concentration, the changing rate of the overall gas holdup with the superficial gas velocity and/or the solid concentration is lower. Furthermore, it is observed that the effect of the solid particle diameter on overall gas holdup is negligible.

1. Introduction

Slurry bubble column reactors (SBCRs) belong to the general class of multiphase reactors. In these reactors, a gas is injected from a sparger and bubbles are dispersed through a slurry in a vertical cylindrical column. SBCRs are becoming more competitive due to their inherent advantages and are used in numerous industrial applications. Although SBCRs are simple in construction, accurate and successful design and scale-up of such reactors require a thorough understanding of the prevailing hydrodynamic characteristics at conditions similar to the targeted process.

Gas holdup is a dimensionless parameter that is used to design bubble column systems (Luo et al., 1999). It represents the volume of gas phase (bubbles) relative to the total volume of slurry and gas inside the column. The behavior of the gas holdup has been attributed to many different factors, including the physical properties of the gas/liquid/solid phase, reactor size, gas distributor design, and the operating variables, i.e. pressure, superficial gas velocity, temperature, and solid loading. However, due to the complex interaction among the various phases, the flow field and hydrodynamics of the SBCR have not yet been well understood.

All past studies examined gas holdup because it plays an important role in design and analysis of bubble columns. As reported by Li and Prakash (2000), in a three-phase slurry bubble column, the gas holdup $\left(\alpha_g\right)$ along the bed height can be expressed as;

$$\alpha_g = 1 - \frac{\Delta P}{\rho_{sl} g \Delta H} \quad \text{for} \quad \rho_{sl} >> \rho_g \tag{1}$$

where ρ_g and ρ_{sl} are the gas and slurry densities, respectively, g is the gravitational acceleration and ΔH and ΔP are the height and pressure differences between the transducers, respectively. Eq. (1) can be directly applied for estimation of gas holdup in a slurry bubble column.

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http://dx.doi.org/10.1016/j.cherd.2016.02.032
0263-8762/

Nomenclature

C_s	Volumetric solid concentration
d_o	Orifice diameter (m)
d_P	Particle diameter (m)
D_R	Diameter of reactor (m)
g	Gravitational acceleration (m^2/s)
H	Height of static liquid (m)
H_R	Height of reactor (m)
Re	Reynolds number
U_{gs}	Superficial velocity of gas (m/s)
We	Weber number

Greek Letters

α_g	Gas holdup
ΔH	Height difference between transducers (m)
ΔP	Static pressure drop (Pa)
μ_g	Dynamic viscosity of gas phase (Pa.s)
μ_{sl}	Dynamic viscosity of slurry phase (Pa.s)
α_g	Density of gas (kg/m^3)
ρ_{sl}	Density of slurry (kg/m^3)
σ	Surface tension (N/m)

For both bubble columns and slurry bubble columns, gas holdup has been found to increase with increasing superficial gas velocity (Cho et al., 2002, Behkish, 2004, Prakash et al., 2001, Li and Prakash, 2000, Krishna et al., 1997, Reilly et al., 1994, Hyndman et al., 1997, Daly et al., 1992, Pino et al., 1992, Krishna et al., 1991, Saxena et al., 1990, Schumpe and Grund, 1986, Deckwer, 1980). In spite of the differences in the investigated systems, all studies have reported that the gas holdup increases with increasing superficial gas velocity.

The effect of column diameter and height on hydrodynamics is widely investigated in the literature. Many investigators have reported that gas holdup levels off when column diameters are larger than 0.15 m (Wilkinson et al., 1992, Shah et al., 1982, Akita and Yoshida, 1973, Yoshida and Akita, 1965, Fair et al., 1962). Luo et al. (1999) reported that the influence of the column height is insignificant if the height is above 1–3 m and the ratio of the column height to the diameter (aspect ratio) is larger than 5. Several studies have concluded that the effect of the gas sparger on gas holdup is minimum when the holes diameters are larger than 1–2 mm (Jordan and Schumpe, 2001, Wilkinson et al., 1992, Akita and Yoshida, 1973).

The effect of solid concentration on gas holdup has been investigated by a number of researchers. Several researchers concluded that an increase in solids concentration generally reduced the gas holdup (Krishna et al., 1997, Li and Prakash, 1997, Pino et al., 1992, Koide et al., 1984, Sada et al., 1984, Kara et al., 1982, Deckwer, 1980, Kato et al., 1973). Sada et al. (1984) also reported that for low solids loading (<5 vol.%), the behavior of the slurry bubble column is close to that of a solid-free bubble column. On the contrary, Kara et al. (1982) found a strong dependence of gas holdup on solids concentration at low solids concentrations. Kato et al. (1973) reported that the effect of solid concentration on gas holdup becomes significant at high gas velocities (>10–20 cm/s). The system of slurry bubble column with alumina–water slurry and helium gas has been investigated experimentally by Abdulrahman (2015, 2016a) to examine the direct contact heat transfer and the flow regime transition velocity, respectively. Abdulrahman (2016b) has also investigated the direct contact heat transfer in the alumina–water–helium system by using CFD analyses.

In spite of the different systems and parameters that were investigated in the studies of gas holdup, most of these studies, as well as empirical correlations for predicting gas holdup, were limited to ambient conditions and to air/aqueous solutions, and did not consider the effect of gas/liquid nature. In the literature, no study has been found regarding detailed gas holdup investigations of SBCR with high temperature helium gas. Therefore, this lack motivates the present work, which seeks to fill this gap by investigating experimentally the SBCR using alumina–water slurry at 22 °C and helium gas at 90 °C. The importance of using helium gas lies in being a perfect fluid for transferring heat because of its high-specific heat as well as being inert and safe to use. It is well known that the gas density plays an important role in the hydrodynamic of bubble columns. Since the density of the helium gas at 90 °C is less than that of air at ambient temperature by more than nine times, the use of previous literature results and correlations for predicting gas holdup of a high temperature helium gas in SBCR can be risky. In general, there are many advantages of using slurry bubble column reactors with high temperature helium gas that motivates doing more detailed studies with this type of reactors. The advantages include better temperature control, lower pressure drop, and excellent heat transfer rates per unit volume of the reactor. Additional advantages are, higher values of effective interfacial areas; little maintenance required due to simple construction; and relatively cheap to construct and operate and require less floor space.

2. Experimental work

2.1. Experimental setup

The schematic of the SBCR setup is illustrated in Fig. 1. All experiments were conducted in a stainless steel column with 21.6 cm inner diameter and 91.5 cm height. The diameter of the reactor was chosen to be larger than 15 cm to minimize its effect on hydrodynamic studies. The reactor consisted of four sections provided with flanges for easy construction and flexibility and also for easy installation and removal for cleaning purposes. The reactor was provided with two Jerguson site-windows, located in the middle of the second section from the bottom of the reactor. These windows were placed in opposite directions to allow the light to penetrate through one of the windows in order to enable a clear vision for the bubbles behavior under a given operating condition. A ball valve was installed at the bottom of the column to drain the slurry and clean the column. The column wall was thermally insulated to reduce heat losses from the column wall.

There are four pressure transducers, provided by OMEGA (PX209-30GI), mounted to pressure taps at different locations on the reactor, which allow the measurement of the hydrostatic pressure head at any level in the reactor. The locations of the pressure transducers are 21, 42.5, 61.6 and 80.6 cm above the bottom of the column. The four transducers could measure pressures up to 207 kPa and their operating temperature range is from -54 to 121 °C. The accuracy of the pressure transducer is 0.25% full scale (including linearity, hysteresis and repeatability) and the output signal is electrical current (4–20 mA). Six quick disconnect thermocouples of type K with removable standard size connectors were arranged at different distances inside the column to measure the temperature along the