Chemical Engineering Science 157 (2017) 99–106

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Hydrodynamic characteristics at the layer inversion point in three-phase fluidized beds with binary solids

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HIGHLIGHTS

- Examine layer inversion in gas–liquid–solid fluidized beds with binary solids.
- Liquid layer-inversion velocity increases at initial bed contraction.
- Liquid layer inversion velocity decreases at initial bed expansion behavior.

ARTICLE INFO

Article history:
Received 22 August 2015
Received in revised form
3 November 2015
Accepted 20 November 2015
Available online 29 November 2015

Keywords:
Three phase fluidization
Binary solids
Layer inversion
Pressure gradient variation
Bed expansion and contraction

ABSTRACT

Layer inversion in gas–liquid–solid fluidized beds with binary solids was examined in a semi-acrylic column of 1.8 m height and 0.21 m inner diameter. Binary solid combinations were composed of polymer beads (PB, d_p=3.3 mm, ρ_s=1,280 kg/m^3) and glass beads (GB, d_p=0.385 mm, ρ_s=2500 kg/m^3). Five volumetric ratios (PB:GB=0.67:0.33, 0.6:0.4, 0.5:0.5, 0.4:0.6, 0.33:0.67) were used with superficial liquid velocities of 21.6–34.2 mm/s, and superficial gas velocities of 0 to 16.6 mm/s. Bubble size, bed height, and superficial liquid velocity at the layer inversion point vary with the binary composition. Upon gas introduction into a liquid–solid fluidization column, the superficial liquid layer-inversion velocity increased if it occurred when there was initial bed contraction. On the other hand, the liquid layer inversion velocity decreased when there was initial bed expansion. For all binary solid combinations showing initial bed expansion, liquid layer-inversion velocity decreased with increasing superficial gas velocity in three-phase fluidization, consistent with the gas-perturbed liquid model.

1. Introduction

Three-phase fluidized beds have been widely used in the chemical industry for such applications as bioreactors, Fischer–Tropsch synthesis, wastewater treatment, and mineral separation (Epstein, 2003). Recently, a chemical reaction, using binary solids differing in size and density in ethanol with a ferrieirite catalyst and synthesis gas, demonstrated the application of layer inversion in three-phase fluidized beds (Bae et al., 2012).

Layer inversion was first reported by Hancock (1936) in liquid–solid fluidized beds. When the superficial liquid velocity is lower than the layer-inversion velocity, clear layers of two components occur where denser particles (or particle mixtures) are at the bottom of the bed and less dense particles are at the top. As the bulk densities of the two mixed solid components equilibrate with increasing superficial liquid velocity, the two components become homogeneously mixed at the "layer inversion point." Escudié et al. (2006) evaluated more than 20 layer inversion models of liquid–solid fluidized beds, but layer inversion of gas–liquid–solid fluidized beds has received only limited attention (Fan et al., 1985; Chun et al., 2011; Rim et al., 2013, 2014).

Chun et al. (2011) and Rim et al. (2013, 2014) measured the layer inversion point in liquid–solid and gas–liquid–solid fluidization by means of an index introduced by Brereton and Grace (1993) for gas–solids circulating fluidized beds. Chun et al. (2011) analyzed the layer-inversion velocity determined by the mixing index, using the gas-perturbed liquid model of Zhang et al. (1995). Chun et al. (2011) generalized the model, written by Rim et al. (2013) as:

$$U_{Li,inv} = \frac{U_l'')_{inv}}{\varepsilon_l'')_{inv}} = \frac{U_l''')_{inv}}{\varepsilon_l''')_{inv}} \quad (1)$$

i.e. by assuming that the interstitial liquid velocity at the layer inversion point is the same in corresponding liquid–solid and gas–liquid–solid systems. Rim et al. (2013) predicted the layer

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http://dx.doi.org/10.1016/j.ces.2015.11.021
0009-2509/

inversion velocity in three-phase fluidization using Eq. (1). In their study, Rim et al. (2013) used polymer beads and glass beads as bed materials, but their experiments were conducted with only one binary volumetric composition, PB:GB = 0.53:0.47. Therefore, the hybrid model by Rim et al. (2013) did not explain the effect of bed expansion or contraction in relation to the volumetric ratio of polymer beads and glass beads. In addition, when the superficial gas velocity is constant, the gas perturbed liquid model does not account for the shape of bubbles which change their form according to the size and density of the solids.

Zhang et al. (1995) implicitly assume that injecting gas at a certain liquid velocity causes homogeneous mixing. However, in reality, bubbles form wakes at the inversion point. In the initial bed contraction regime, small bubbles coalesce, and the wakes behind the bubbles elevate liquid and solids components. Therefore, we cannot entirely explain layer inversion in the presence of initial bed expansion or contraction by means of the gas-perturbed liquid model.

Hydrodynamic characteristics and liquid layer-inversion velocity corresponding to various operating conditions are analyzed in this paper. The bed height variation with gas velocity for each solid volume fraction is investigated and the hydrodynamic characteristics in three-phase fluidization are analyzed. Operating variables are the volumetric ratios of binary solids, gas velocity, and liquid velocity at the layer-inversion point.

2. Experimental

Fig. 1 shows a schematic diagram of the experimental set-up utilized in this study. Liquid holdup at the layer inversion point was measured in a 0.21 m inner diameter semi-cylindrical, 1.8 m tall acrylic fluidization column with binary solid mixtures of polymer beads (PB, d_p = 3.3 mm, ρ_s = 1,280 kg/m^3) and glass beads (GB, d_p = 0.385 mm, ρ_s = 2,500 kg/m^3). Fixing H_{B0}/D_H to ∼3, the volumes of polymer beads and glass beads were changed to provide pre-determined PB:GB ratios. Physical properties of the experimental monocomponent and binary solid mixture combinations are given in Table 1. Gas and liquid distributors were positioned at the bottom of the test section, providing uniform flows of both liquid and gas. The liquid and gas distributors had 35 holes of 3 mm diameter and 33 holes of 1 mm diameter, respectively. Tap water and ambient air were the liquid and gas, respectively. The temperature of the liquid was maintained at 20 ± 2 °C by a cooling apparatus.

The pressure drop across the bed was measured by a differential pressure transducer (OMEGA PX771A), connected to pressure taps, located axially and flush with the wall of the column. Pressure taps were installed horizontally at 0.05 m intervals to a height of 0.365 m, and then at 0.1 m intervals to 1.665 m, starting at 0.065 m above the liquid distributor. Transmitter signals were processed by a personal computer at a sampling frequency of 10 Hz for 60 s time intervals. The axial pressure drop measurements were performed under steady state conditions.

At the layer-inversion condition, the binary solids are completely mixed, axial uniformity of solids holdup is achieved, and solids holdup can be simply defined as solids volume, written in terms of the densities and masses of binary solids, divided by the bed volume.

$$\varepsilon_s = \frac{\frac{M_1}{\rho_{s,1}} + \frac{M_2}{\rho_{s,2}}}{\frac{1}{2}\bullet\frac{1}{4}\pi D_H^2 H_B} \tag{2}$$

Eq. (2) is suitable for both liquid–solid and gas–liquid–solid fluidization. For liquid–solid fluidization, liquid holdup, ε_l, is definitely 1-ε_s. Note that H_B in Eq. (2) is obtained via the pressure profile as opposed to visually. However, in the case of gas–liquid–solid fluidization, three equations are needed:

$$\varepsilon_s + \varepsilon_l + \varepsilon_g = 1 \tag{3}$$

$$-\frac{dP}{dZ} = \left(\varepsilon_s\overline{\rho}_s + \varepsilon_l\rho_l + \varepsilon_g\rho_g\right)g \tag{4}$$

$$\overline{\rho}_s = X_1\rho_{s1} + X_2\rho_{s2} \tag{5}$$

where X_i is the fluid-free volume fraction of solid species i. Eq. (4) is applies only when layer inversion occurs, at which the pressure gradient in the axial direction is uniform. By simultaneous solution of Eqs. (2)–(5), each phase holdup can be calculated.

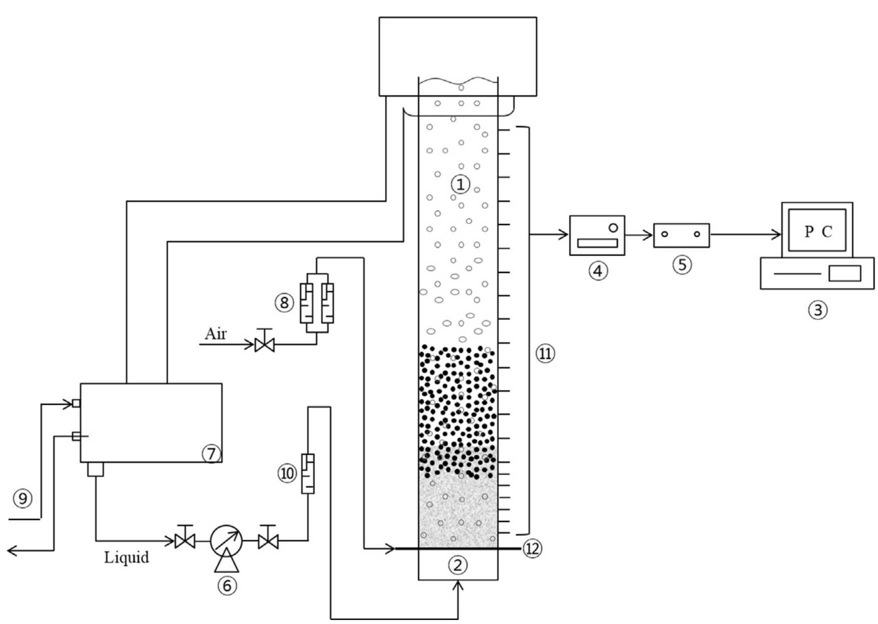

Fig. 1. Schematic of experimental setup: (1) test Section; (2) calming Section; (3) computer; (4) pressure transducer; (5) data acquisition; (6) pump; (7) reservoir; (8) gas flowmeter; (9) from cooler; (10) liquid flowmeter; (11) pressure taps; (12) distributor.