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Experimental investigation of hydrodynamics of liquid–solid mini-fluidized beds

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ABSTRACT

Expanded fluidization behavior in liquid–solid mini-fluidized beds (MFBs) was experimentally investigated using visual measurements. Wall effects in the liquid–solid MFBs were identified and explained. The measured incipient/minimum fluidization liquid velocity (u_{mf}) in the MFBs was 1.67 to 5.25 times higher than that calculated using the Ergun equation when the ratio of solid particle diameter to bed diameter varied from 0.017 to 0.091. The ratio of the Richardson–Zaki (R–Z) exponent obtained by fitting with experimental data to that calculated using the R–Z correlation varied from 0.92 to 0.55. A wider solid particle size distribution resulted in a smaller R–Z exponent. The influence of the solid particle material on u_{mf} and R–Z exponent was negligible.

Introduction

Mini- and micro-fluidized beds are fluidized beds with bed hydraulic diameters on the millimeter or micrometer scale (Doroodchi, Peng, Sathe, Abbasi-Shavazi, & Evans, 2012; Potic et al., 2005; Wang & Fan, 2011). These beds combine the advantages of a fluidized bed and a mini- or micro-system, and are particularly suitable for performing reactions under conditions that would normally lead to mass- and heat-transfer limitations and unsafe operation.

Potic et al. (2005) proposed the concept of micro-fluidized beds for liquid–solid fluidization, and studied the fluidization behavior of solid particle diameters of 60–150 μm in a 1 mm quartz bed. The measured minimum fluidized velocities (u_{mf}) were in good agreement with predictions obtained using the Ergun equation (Ergun, 1952). Doroodchi et al. (2012) examined the fluidization behavior in glass capillary tubes of inner diameters 0.8, 1.2, and 17.1 mm using solid particles of 225 μm, specifically the influence of the wall on the bed hydrodynamics. As the tube diameter decreased, the bed voidage increased sharply, leading to a reduction in the pressure drop across the bed. Zivkovic, Biggs, and Alwahabi (2013) reported an experimental study of liquid–solid fluidization using glass particles of 30 μm in a rectangular fluidized bed with cross-section 400 μm × 175 μm. They found that the glass particles could not be fluidized, because they adhered to the walls. When ethanol was used to replace water as a fluidizing medium, the glass particles were fluidized normally. These phenomena indicate that the surface conditions of the bed inner walls can significantly affect fluidization quality.

Rao, Curtis, Hancock, and Wassgren (2010) studied the effect of bed diameter and height on the minimum fluidization velocities of gas–solid fluidized beds with bed diameters of 16–24 mm and solid particle diameters of 105–600 μm. They proposed a correlation for predicting u_{mf} based on the experimental results. They found that the ratio of the particle diameter to the bed diameter and the ratio of the bed height to the bed diameter both affected u_{mf}; the wall effect is clear when the ratio of the bed diameter to the particle diameter is 40. Wang and Fan (2011) investigated air–fluid catalytic cracking (FCC) particle fluidization in a bed of (0.7–5) mm using particles of 53 μm. They found that gas–solid bubbling fluidization appeared at lower gas velocities than particulate fluidization in beds of 0.7 and 1 mm. Some researchers investigated the intrinsic kinetics of isothermal–differential reactions and complicated fast reactions in gas–solid beds with large bed diameters, i.e., (10–30) mm and particle of 96.4–460.6 μm (Geng et al., 2013; Liu, Xu, & Gao, 2008; Yu et al., 2011; Zeng et al., 2013). The wall effect was clearly observed when the bed diameter to particle size ratio was 50.

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Nomenclature

d	diameter, m
H	bed height, m
H_0	static bed height of solid particles, m
n	Richardson–Zaki exponent
Δp	calculated pressure drop per bed height through bed of particles, Pa/m
$\Delta p'$	measured pressure drop per bed height through bed of particles, Pa/m
R_a	arithmetical mean deviation, m
Re	Reynolds number
R_z	maximum height of profile, m
u	velocity, m/s

Greek letters

ε	voidage
μ	viscosity, Pa s
ρ	density, kg/m^3
Φ_s	degree of sphericity

Subscripts

h	hydraulic
l	liquid phase
mf	minimum fluidization
s	solid (particle) phase
t	terminal in an infinite system
t′	terminal for d_s/D_h

Studies on fluidization in the liquid–solid mini- or micro-fluidized beds are still limited. In particular, the effect of the solid particle size distribution on the fluidization characteristics of miniaturized liquid–solid fluidized systems, which is often encountered in industrial processes and needed to be understood.

In this paper, experiments based on visual inspection of liquid–solid fluidization in mini-fluidized beds (MFBs) were conducted. The effects of the bed diameter and the size and distribution of solid particles on the liquid–solid fluidization characteristics, namely u_{mf} and Richardson–Zaki (R–Z) correlation (Richardson & Zaki, 1954), were studied. The study focused on the effects of the size distribution of solid particles and the bed inner wall on the fluidization behavior in the MFBs; we found no reports of similar studies in the literature.

Experimental setup and procedure

The ratio of the solid particle to the bed diameters (d_s/D_h) indicates the extent to which the wall affects the fluidized bed hydrodynamics. Potic et al. (2005) reported that homogeneous fluidization could be achieved in MFBs resembling a large-scale fluid bed provided d_s/D_h is less than 0.083. However, Rao et al. (2010) reported that the wall effect gradually becomes significant when d_s/D_h is greater than 0.0144. To identify the results of previous studies, we varied d_s/D_h from 0.017 to 0.091 by either changing the bed diameter at a fixed solid particle diameter or varying the solid particle diameter at a given bed diameter.

The MFB experimental apparatus is shown in Fig. 1. For a small bed, observing fluidization behavior inside the bed through a plane transparent wall is more precise, because this avoids the high curvature of a small circular tube. The MFB test section was therefore rectangular (Fig. 1(a)) for the small-diameter bed while cylindrical (Fig. 1(b)) for the large-diameter bed. Foumeny, Moallenmi, Mcgreavy, and Castro (1991) found that the influence of bed ends is negligible if the bed height/diameter is greater than 3.0. In previous studies, the MFBs' height-to-diameter ratios ranged from 4.2 to 22.8 (Liu et al., 2008; Wang & Fan, 2011). Here, in order to eliminate entrance/exit effects on the fluidization behavior in MFBs, the bed height-to-diameter ratios were 6 and 12.7 for the cylindrical and rectangular MFBs, respectively. The hydraulic diameter of the rectangular MFB (D_h) was 3.15 mm (width 4 mm, thickness 2.6 mm, height 40 mm). A disengagement section of width 20 mm was designed to minimize entrainment of solid particles in the rectangular MFB. The liquid distributor at the bottom of the rectangular MFB consisted of a porous plate. A layer of fine mesh with a sieve opening of 47 μm was placed above the distributor to support the solid particles. For the cylindrical MFB, the bed diameter was 11.6 mm, with a total height of 70 mm. A porous plate at the bottom of the MFB was used as the liquid distributor and a layer of the same fine mesh as that in the rectangular bed was placed above the distributor.

The arithmetic mean deviation of the assessed profile, R_a, and the maximum height of the profile, R_z, were measured, using a roughometer (JB-8C, Guangzhou Guangjing Precision Instruments, China), to determine the surface roughnesses of the inner walls of the two MFBs. A higher surface roughness, with $R_a = 1.1 \pm 0.04$ μm and $R_z = 6.16 \pm 0.96$ μm, was obtained for the rectangular MFB; the cylindrical MFB had a low surface roughness, with $R_a = 0.282 \pm 0.003$ μm and $R_z = 1.88 \pm 0.3$ μm.

Glass beads (Dajiang Abrasive Co., Ltd., China) were used as the fluidized solid particles; their properties are shown in Table 1. The solid particle size distribution was determined using a Rise 3000 laser size-measuring apparatus (Rise Size Measurement Co., Ltd., China) with a measurement range from 0.1 to 3500 μm, as shown in Fig. 2.

The terminal velocity of a single particle falling in MFB of 3.15 or 11.6 mm was measured, using a visualization technique, with a high-speed camera (A504k, Basler Vision Technology Co. Ltd., Germany) with a complementary metal-oxide-semiconductor

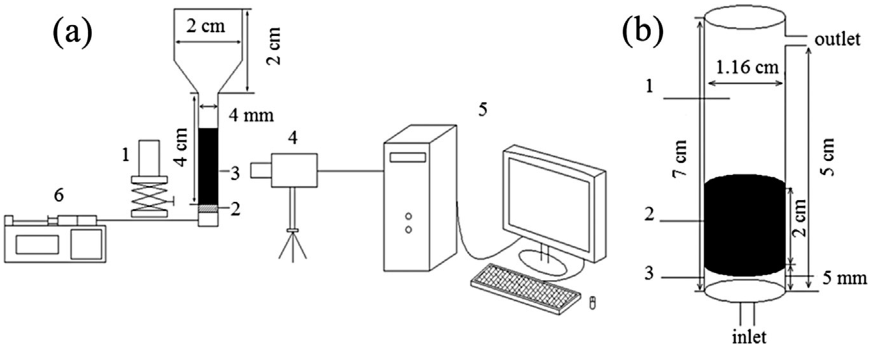

Fig. 1. Schematic diagram of experimental setup for liquid–solid MFB systems: (a) a rectangular channel consisting of 1-light source, 2-liquid distributor, 3-static bed, 4-CMOS camera, 5-PC, 6-syringe pump; and (b) a cylindrical channel consisting of 1-test section, 2-static bed, 3-liquid distribution.