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Mass transfer between bubbles and the dense phase in gas fluidized beds☆

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ABSTRACT

Mass transfer between a bubble and the dense phase in gas fluidized beds of Group A and Group B particles was proposed based on previous experimental results and literature data. The mass transfer coefficient between bubbles and the dense phase was determined by $k_{be} = 0.21d_b$. A theoretical analysis of the mass transfer coefficient between a bubble and the dense phase using diffusion equations showed that the mass transfer coefficient between a bubble and the dense phase is $k_{be} \propto \varepsilon_{mf}\sqrt{Du_b/d_b}$ in both three- and two-dimensional fluidized beds. An effective diffusion coefficient in gas fluidized beds was introduced and correlated with bubble size as $De = 13.3{d_b}^{2.7}$ for Group A and Group B particles. The mass transfer coefficient k_{be} can then be expressed as $k_{be} = 0.492\varepsilon_{mf}\sqrt{u_b d_b^{1.7}}$ for bubbles in a three-dimensional bed and $k_{be} = 0.576\varepsilon_{mf}\sqrt{u_b d_b^{1.7}}$ for bubbles in a two-dimensional bed.

1. Introduction

In gas–solid fluidized beds, bubbles are formed near the bottom of the bed, and exchanges between the gases inside the bubbles and in the dense phase happen all the time as the bubbles rise through the bed. The mass transfer between bubbles and the dense phase plays an important role in fluidized beds of Group A and Group B particles (Geldart, 1973), and is the controlling step for chemical and physical processes taking place in the fluidized beds provided that the chemical reactions or physical processes are fast. Therefore, understanding the mass transfer between bubbles and the dense phase in fluidized beds is important not only for process control but also for fluidized bed design.

The study of the interface mass transfer has used UV absorption techniques (Chavarie & Grace, 1976; Chiba & Kobayashi, 1970; Sit & Grace, 1978), sampling methods (Song, 2004; Song & Xie, 2003, 2006; Wu & Agarwal, 2003), gas sensors (Solimene, Marzocchella, Passarelli, & Salatino, 2006), nuclear magnetic resonance (Pavlin et al., 2007), and injection of an isolated or stream of tracer bubbles. By injecting a stream of tracer bubbles and using UV absorption to measure the tracer concentration (Chiba & Kobayashi, 1970), the mass transfer coefficient in a bubbling fluidized bed of Group B particles was obtained. The mass transfer in a two-dimensional fluidized bed of Group B particles was also investigated by injecting a single tracer bubble (Chavarie & Grace, 1976; Sit & Grace, 1978). In addition, the effect of the bubble's interaction on the mass transfer between bubbles and the dense phase was also investigated by injecting two equally-sized bubbles (Sit & Grace, 1978). For Group A particles, by injecting a single tracer bubble and measuring tracer concentration inside the bubble using a sampling method (Song, 2004; Song & Xie, 2003, 2006), the mass transfer coefficient between a bubble and the dense phase has been obtained.

Two mechanisms of the diffusive and convective transfer between a bubble and the dense phase have been modeled theoretically, and interaction factors have been introduced to modify the mass transfer coefficient as the sum of the two mechanisms, as reviewed by Sit and Grace (1978). Although agreement was excellent for some individual cases, none of these models gave consistently good results over the whole range of particle sizes examined. From the diffusion equation around a bubble, Song and Xie (Song, 2004; Song & Xie, 2006) derived a mass transfer coefficient by considering the turbulence caused by the particle's flow in the dense phase. An effective diffusion coefficient in a fluidized

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A	integral constant, kmol/m^3
a_b	bubble's surface area based on projected bubble size per unit bubble volume, m^{-1}
b	parameter given by Eq. (17), m
c	tracer concentration, kmol/m^3
c_b	tracer molar concentration inside bubble, kmol/m^3
c_e	tracer molar concentration in the dense phase, kmol/m^3
C	bubble velocity constant defined by Eq. (4)
D	molecular diffusion coefficient, m^2/s
De	effective molecular diffusion coefficient in the dense phase, m^2/s
d_b	projected bubble size, m
d_{bh}	pierced bubble size, m
d_{bv}	bubble volume size, m
g	gravitational acceleration, m/s^2
k_{be}	mass transfer coefficient between a bubble and the dense phase, m/s
L	width of two-dimensional bed, m
N_b	gas exchange between a bubble and the dense phase, kmol/s
r	radial distance in spherical and cylindrical coordinates, m
r_b	radius of projected bubble, m
u_b	bubble velocity, m/s
u_θ	tangential velocity of gas around a bubble, m/s
x_b	tracer volume fraction inside a bubble

Greek letters

β_w	volume fraction of bubble wake
ε_{mf}	voidage at the incipient fluidization
η	normalized variable parameter defined by Eq. (10)
θ	inclination angle in spherical and cylindrical coordinates, rad
τ	bubble residence time, s

bed was introduced, and the results showed that the effective diffusion coefficient could be correlated well with the bubble's Reynolds number.

In this paper, the mass transfer coefficient between a bubble and the dense phase in gas fluidized beds of Group A and Group B particles, and a correlation of the effective diffusion coefficient with the bubble size are proposed based on previous experimental results (Song, 2004; Song & Xie, 2003) and literature data (Chavarie & Grace, 1976; Chiba & Kobayashi, 1970; Sit & Grace, 1978) and on a theoretical analysis from diffusion equations (Song, 2004; Song & Xie, 2006).

2. Experimental

For Group A particles, the mass transfer between a bubble and the dense phase was investigated by injecting a single tracer bubble (Song, 2004; Song & Xie, 2003) in a three-dimensional fluidized bed and a two-dimensional fluidized bed. The three-dimensional fluidized bed was a 0.182 m diameter Perspex column, 1 m tall equipped with a 0.2 m steel bottom section and a high pressure-drop distributor. The distributor was made up of ten layers of filter paper glued at the edges and supported by a coarse sieve to give a pressure drop of approximately 0.6 m H_2O at a superficial velocity of 1 cm/s. The two-dimensional fluidized bed was made up of Perspex, 0.3 m in width, 0.01 m thick and 1 m tall. The distributor was a fixed bed 0.3 m tall filled with 300 μm glass beads, which gave a

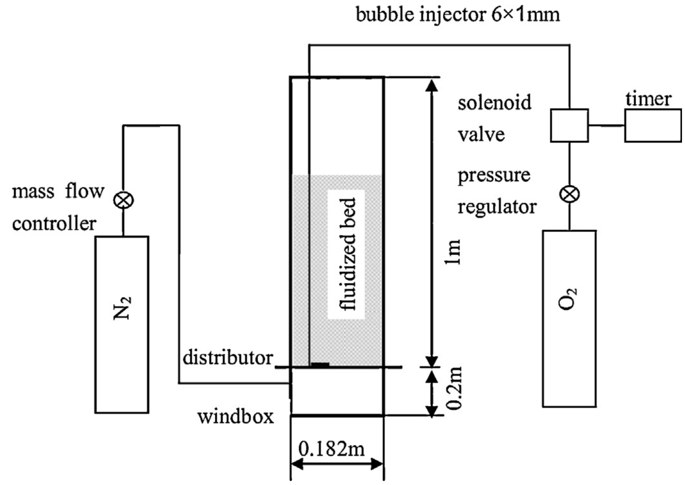

Fig. 1. Illustration of the experimental apparatus used in this study.

pressure drop of approximately 0.2 m H_2O at a superficial velocity of 1 cm/s.

Nitrogen was used as the fluidizing gas and was measured and controlled by a mass flow controller to give a superficial velocity just above the minimum fluidization velocity of the particles. Oxygen was used as the tracer gas and was introduced into the bed by a solenoid valve controlled by a timer to generate a single bubble. The bubble generator was a 6 mm × 1 mm stainless steel tube bent at a right angle at the bottom and rested on the distributor. The size of a generated bubble was controlled by the opening time of the solenoid valve set by the timer. The gauge pressure of the oxygen cylinder was keep at 0.1 bar. A 0.1–0.5 s opening time of the solenoid valve provided a bubble size from 3 to 10 cm for the present experiments. The experimental apparatus is illustrated in Fig. 1.

Four batches of FCC particles were used in the experiments. They were prepared by sieving an original batch, with median sizes ranging from 50 to 90 μm. The particle properties of median size, particle density, minimum fluidization and minimum bubbling velocities of the four FCC particles are given in Table 1.

The projected bubble size was measured visually at the top of the bed when a bubble burst out at the bed surface for the bubbles in the three-dimensional fluidized bed, and it was measured visually from a side of the two-dimensional fluidized bed. The residence time of a bubble in the bed was measured by a stopwatch, and its rise velocity was then obtained by the known bed height. The gas inside a generated bubble was sampled by an injector at the top of the bed surface when the bubble burst out. The sampling duration was restricted within 1 s to minimize the mixing effect caused by freeboard gas, and approximately 5–10 mL gas was sampled each time. The oxygen volume fraction of a sample was measured by an oxygen analyzer (CYS-1). The response time of the analyzer was 15 s, and the measurement range of the analyzer was 0–100%. The resolution of the analyzer was ±0.7% in the measurement range of 0–25% and was ±2.5% in the measurement range of 25%–100%. In the experiments, a few replicates of each sample were taken, and

Table 1
Physical properties of particles used in the experiments.

Particles	$d_{50\%}$ (μm)	Bulk density(kg/m^3)	u_{mf} (m/s)	u_{mb} (m/s)
FCC1	70	721	0.0053	0.0107
FCC2	53	840	0.0021	0.0065
FCC3	93	686	0.0108	0.0192
FCC4	55	747	0.0037	0.0065