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Numerical investigation of gas bubble behavior in tapered fluidized beds

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ABSTRACT

In this article, the behavior of gas bubbles in tapered fluidized beds is investigated with the use of a two-fluid model incorporating kinetic theory of granular flow. The effects of various parameters such as apex angle, particle size, and particle density on the size distribution and the rise velocity of gas bubbles were examined. In addition, the simulation results for the bubble fraction and axial velocity of gas bubbles were compared with experimental data reported in the literature and good agreement was observed. As the apex angle was increased, the fraction of gas bubbles with large sizes increased and the fraction of bubbles with small sizes decreased. As the particle size increased, the fraction of gas bubbles with large diameters decreased; however, the fraction of bubbles with medium diameters increased. The obtained results clearly indicate that an increased solid density increased the bubble rise velocity up to a specified height and reduced the velocity at larger heights, in tapered fluidized beds.

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Introduction

Fluidization is the phenomena of solid particles showing fluid-like behavior from the introduction of a fluid to the solid. Owing to the special characteristics created by contact between the solid and fluid phases, fluidized beds are appropriate for various industrial processes, such as biological treatment of wastewater, immobilized biofilm reactions, coal gasification, liquefaction, and catalytic polymerization (Olazar, San Jose, Aguayo, Arandes, & Bilbao, 1992; Peng & Fan, 1997). Although most studies concerning fluidized beds have been conducted for columnar configurations, a new configuration, known as a tapered or conical fluidized bed, has been proposed in recent decades. In tapered fluidized beds, the fluid velocity at the bottom of the bed is high enough to ensure fluidization of large particles. In addition, the decreasing fluid velocity in the axial direction prevents entrainment of small particles in the fluid phase.

Because of their more stable pressure, conical fluidized beds can operate smoothly without any instabilities. This type of fluidized bed can be useful and beneficial for fluidization of solids with wide size and density distributions. Experimental examinations of the hydrodynamic behavior of tapered fluidized beds have been performed by Shi, Yu, and Fan (1984). The liquid and solid flow patterns and bed pressure drop for different superficial velocities of the fluid phase were studied. The hydrodynamic characteristics of tapered fluidized beds were experimentally determined, including the minimum velocity of partial and full fluidization, and the maximum bed pressure drop.

Important aspects of the dynamics of conical fluidized beds were explored by Biswal, Sahu, and Roy (1982). They conducted an experimental study of the fluctuation ratio for regular particles, and also determined correlations of the fluctuation ratio with particle diameter, bed diameter, static bed height, and the mass velocity of the fluid. A study on the hydrodynamic behavior of gas and solid phases was conducted by Lu, Zhao, Shen, Ding, and Jin (2006). They applied a two-dimensional two-fluid model (TFM) to simulate columnar and tapered risers. It was reported that the distribution of the solid volume fraction in the tapered risers was more uniform than that in columnar risers. Furthermore, the angle of the incline played a crucial role in the uniform distribution of the particles in the tapered risers.

Markowski (1992) used a conical jet-spouted bed dryer with inert particles to dry animal blood plasma. The influence of operating conditions on the final moisture content, product properties, and the throughput of the dryer were examined. It was found that the feed rate was the most important parameter affecting the efficiency and stability of the process. Passos, Massarani, Freire, and Mujumdar (1997) used a conical spouted bed with inert particles

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Nomenclature

A_{T}	Total area of bubble, m^2
C_{D}	Drag coefficient
d_{s}	Particle diameter, m
D_{b}	Equivalent bubble diameter, m
e_{ss}	Particle–particle restitution coefficient
f	Drag correlation parameter
Fr	Empirical constant, Pa
$\vec{g}$	Gravitational acceleration, m/s^2
$g_{0,\mathrm{ss}}$	Radial distribution function
H_0	Static bed height, m
$\bar{\bar{I}}$	Unit stress tensor
$I_{2\mathrm{D}}$	Second invariant of the deviatory stress tensor, s^{-2}
$k_{\theta_{\mathrm{s}}}$	Diffusion coefficient of granular energy, kg/(m s)
K_{sf}	Momentum exchange coefficient between fluid and solid phases, $kg/(m^3\,s)$
n, p	Empirical constant
p	Pressure, Pa
Re_{s}	Relative Reynolds number
S_{s}	Solid phase source term, Pa/m
t	Time, s
$\vec{v}$	Local velocity, m/s
$v_{\mathrm{r,s}}$	Ratio of terminal velocity of a group of particles to that of an isolated particle
y	Vertical distance from the fluid distributor, m

Greek symbols

α	Volume fraction
$\gamma_{\theta_{\mathrm{s}}}$	Collisional dissipation of energy, $kg/(m\,s^3)$
Δp	Bed pressure drop, Pa
θ_{s}	Granular temperature, m^2/s^2
λ	Bulk viscosity, Pa s
μ	Shear viscosity, Pa s
ρ	Density, kg/m^3
$\bar{\bar{\tau}}$	Stress tensor, Pa
τ_{s}	Particulate relaxation time, s
ϕ	Angle of internal friction, °
φ_{fs}	Net transfer rate of the fluctuation energy between fluid and solid phases, $kg/(m\,s^3)$

Subscripts/superscripts

col	Collisional
f	Fluid phase
kin	Kinetic
max	Maximum
min	Minimum
q	Solid/gas phase
s	Solid phase

to dry paste-like materials. The drying performance of the pastes was evaluated as a function of the dimensions of the spouted bed, the paste properties, and the characteristics of the fluid flow. Pham (1983) used a conical spouted bed dryer with hot air as a medium for drying animal blood into a powder with little thermal degradation. The spouting and drying performances of the dryer were also investigated and a model of the drying process was developed to predict variations in the maximum throughput and product properties with changes in operating conditions.

Pyrolysis is a procedure used to recycle plastics and obtain feedstocks and fuel. Fluidized bed reactors are currently the most developed technology for coating inert particles with fused plastic. Because of particle agglomeration provoked by fusion of plastic-coated particles, defluidization in columnar fluidized beds causes problems on a large scale. To avoid these problems, the thickness of the fused plastic that coats the particles must be minimized and the particle/plastic ratio controlled. However, these precautions seriously limit the yield of the reactor. A conical spouted bed is a new kind of fluidized bed. The conical geometry enables great control over the gas flow rate, which can be increased from a spouted bed to jet spouted regime. Consequently, operations can be performed over a wide bed-voidage range and the intensity of the gas–solid contact can be increased. Despite the increase in gas and particle velocities, the characteristic cyclic movement in a spouted bed is maintained (Aguado et al., 2005).

Aguado, Olazar, San José, Aguirre, and Bilbao (2000) studied the pyrolysis of sawdust with inert gas (N_2) in the temperature range 350–700 °C in a conical spouted bed reactor. They examined the influence of pyrolysis temperature on char properties, gas and liquid composition, and yields of gas, liquid, and char. Aguado, Olazar, San José, Gaisán, and Bilbao (2002) investigated the pyrolysis of polyolefins in a conical spouted bed reactor and determined the kinetics of wax formation and individual gaseous products. A study on the effect of HZSM-5 zeolite catalyst for flash pyrolysis of sawdust at 400 °C in a conical spouted bed reactor was conducted by Atutxa, Aguado, Gayubo, Olazar, and Bilbao (2005). In this study, the kinetic constants of the catalytic pyrolysis of biomass were also determined. It was found that as the mass of catalyst increased, the yield of gases increased, the liquid yield markedly increased, and the char yield decreased slightly.

The dynamic characteristics of heterogeneous and homogeneous binary mixtures of irregular particles in tapered fluidized beds were examined by Sau, Mohanty, and Biswal (2008a, 2008b). They conducted an experimental study and measured the critical fluidization velocity and bed pressure drop for various taper angles. In addition, they applied dimensional analysis to derive correlations for critical fluidization velocity and bed pressure drop. Chalermsinsuwan, Kuchonthara, and Piumsomboon (2010) simulated tapered and columnar circulating fluidized bed risers. They also predicted the hydrodynamic behavior and turbulence specifications of the fluidized beds. It was found that tapered-out risers improved the turbulence and mixing phenomena, and tapered-in risers provided a better distribution of temperature and increased the residence time of particles.

Lopez et al. (2010) studied the continuous pyrolysis of waste tires under vacuum conditions, i.e., 25 and 50 kPa, in a pilot plant equipped with a conical spouted bed reactor to examine the effects of vacuum on product distribution and properties. Erkiaga, Lopez, Amutio, Bilbao, and Olazar (2014) used a conical spouted bed reactor to gasify pinewood sawdust using steam as a gasifying agent. They studied the effects of the steam/biomass ratio, temperature, and sawdust particle size on the distribution of products and their composition. Du, Yang, Berrouk, Yang, and Al Shoaibi (2014) developed a computational fluid dynamics (CFD)-based equivalent reactor network (ERN) model to simulate the gasification process of polyethylene in a pilot-scale conical spouted bed. They used their CFD-based ERN model to investigate the effects of gasification temperature and equivalence ratio on the gasification performance of polyethylene.

The hydrodynamic characteristics of a tapered fluidized bed, including minimum fluidization velocity and the minimum velocity of full fluidization, were experimentally studied by Gan, Lu, and Wang (2014). They investigated the effects of taper angle, particle size, and static bed height. They found that both the minimum fluidization velocity and the minimum velocity of the full fluidization increased as the taper angle, static bed height, and particle size were increased. Zhao et al. (2014) examined the hydrodynamic behavior of tapered fluidized beds without a gas distributor. They reported that the gas–solid flow regimes could be divided vertically

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