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Powder attrition in gas fluidized beds

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ABSTRACT

New developments of fluidized beds are focusing on their use in powder circulation systems for thermal energy capture, storage and re-use. Although fast particle motion and associated high degree of mixing favor the high rate of heat transfer in fluidized beds, they however cause inter-particle collision and bed-to-wall impacts, both leading to particle attrition. Experimental work on attrition was carried out in batch gas fluidized beds of 6.62 cm and 10 cm I.D. The rate of attrition was determined both for bubbling fluidized bed conditions, and when adding jet-orifices above the distributor. The attrition was determined from the variation in composition of bed material and collected carryover. A literature survey determined the dominant fluidization parameters, including operating superficial gas velocity, orifice velocity and size, bed weight and diameter, and particle characteristics. Analysis of the experimental findings resulted in a correlation that encompasses all relevant operating characteristics. As a result, the attrition rate can be correlated as the sum of the bubble-induced and jet-induced contribution: $R_t = K_1[\gamma(U-U_{mf}) \cdot \frac{W}{D}] + K_2[n_{or} \cdot {d_{or}}^2 \cdot {U_{or}}^2]$ with K_1 and K_2, the intrinsic attrition rate constants, being mainly a function of particle characteristics. K_1 is ~10^{-5} for soft, ~10^{-6} for hard and ~10^{-7} for very hard particles, respectively. K_2 is ~10^{-5} for silica sand. In general, attrition is negligible at low superficial gas velocities, but significantly increases through the jet-induced contribution if the orifice velocity exceeds ~30 m/s.

Nomenclature

A	cross-sectional area of the bed	m^2
AI	abrasive index number (CEMA)	–
D	diameter of the bed	m
d_p	particle size	μm
d_{or}	the inside diameter of a single orifice	mm
d_{sv}	surface-to-volume diameter	μm
H	height of the bed	m
H_{mf}	height of the bed at minimum fluidization	m
HM	Moh's hardness	–
K_1	intrinsic constant for bubble-induced attrition	–
K_2	intrinsic constant for jet-induced attrition	kg s/m^4
K_f	fracture toughness	N/$m^{3/2}$
n_{or}	the number of orifice (jets)	–
Q_B	visible bubble flow rate	m3/s
R_t	attrition rate at time t	kg/s
t	time	s
U_c	velocity at cyclone inlet	m/s
U_s	superficial velocity of fluidizing gas with distributor only	m/s
U_j	superficial velocity of fluidizing gas with single nozzle system only	m/s
U	the total superficial velocity of gas ($=U_s + U_j$)	m/s
U_{mf}	minimum fluidization velocity	m/s
U_{or}	velocity of gas at exit of each orifice	m/s
W	total bed weight	kg
γ	bubble through flow factor	–
ρ_p, ρ_B	absolute particle density and bulk density of the bed, respectively	kg/m^3
σ	fracture energy (force/length)	N/m

1. Introduction

New developments of fluidized beds are focusing on their use in powder circulation systems for thermal energy capture, storage and re-use [1–4]. In these systems, mostly Geldart A and B type powders are used at low to moderate velocities, corresponding to a U/U_{mf}-ratio below 3 to 5.

Powders envisaged include sand, silicon carbide, limestone or alumina. Since such systems are supposed to operate on a continuous basis, without particle degradation or loss, the investigation of attrition is very important. A typical illustration of such a powder loop is provided in Fig. 1.

The depicted powder circulation loop involves different gas–solid contacting modes. The upflow bubbling fluidized bed in the solar energy receiver is combined with moving beds in the hot and cold storage hoppers, a moving bed evaporator and superheater, a bubbling fluidized bed economizer, and different mechanical powder conveyors (screw conveyors, elevators) to connect the different sub-systems and to overcome the height difference.

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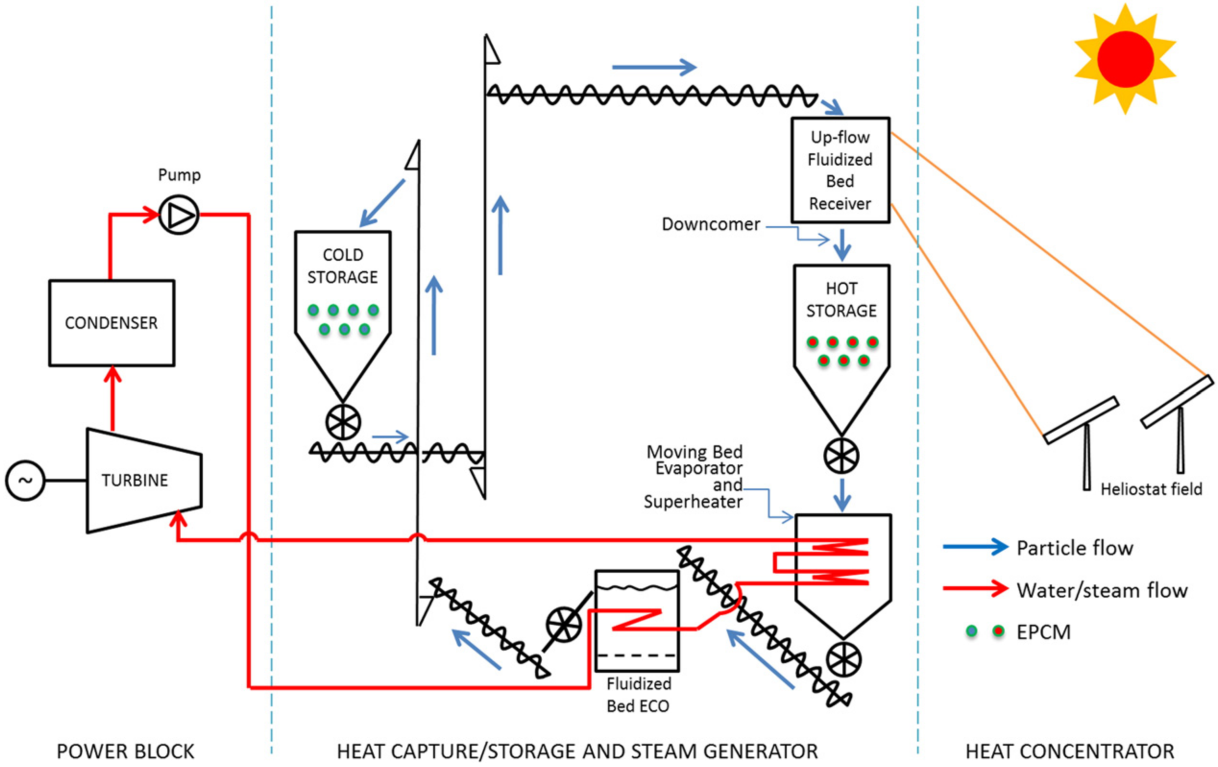

Fig. 1. Layout of a concentrated solar power plant (CSP) plant with powder circulation loop.

Although fast particle motion and associated high degree of mixing favor the use of fluidized beds, they however cause inter-particle collision and bed-to-wall impacts, both leading to particle attrition. Attrition generates fines that can be lost in the dust collection system, whereas the particle size distribution of the bed will alter during the operation. If fines are not recycled to the bed, bed material will gradually get coarser; if recycled, the bed particle size distribution may get too fine. Evaluating attrition is hence important in fluid-bed systems for a controlled process operation, i.e. (i) to limit the generation of fines; (ii) to minimize down-stream deposits or erosion, (iii) to possibly apply a controlled attrition to maintain material reactivity, as in sludge combustion; (iv) to respect environmental regulations (i.e. minimize fine particle collection cost) and (v) to reduce the loss of bed material.

Attrition of fluid-bed solids can be caused by several mechanisms, including thermal stress, chemical stress, static mechanical stress and kinetic stress, as illustrated in Table 1 and Fig. 2. Erosion is linked to the effect of moving particles upon the construction materials of the equipment, and is not considered in the present paper.

The paper deals with zones A and B only. The present work focuses on both the kinetic and the static mechanical stress, which combine the effects of (i) slow-moving particles subject to surface abrasion upon collision, (ii) fast-moving particles subject to surface abrasion upon collision, and/or (iii) fast-moving particles fracturing completely near high-velocity jets.

Table 1
Sources of attrition (Vaux and Keairns [5]).

Sources of powder attrition	
Mechanical stress	Screw feeder; rotary valves, etc.
Kinetic stress	Impact of particles due to high velocity jets (orifices); in conveying lines; due to bubbling action; collision with tubes, baffles, wall; in cyclones, etc.
Thermal stress	Thermal shock of cold particles fed in a hot bed
Chemical stress	Evolving gases, water vapor, …

The findings hence differ entirely from results of Xiao et al. [6] and Chen et al. [7] (high velocity jet apparatus), Chen et al. [8] (circulating fluidized bed attrition), or Scala and Salatino [9] (attrition during calcination and sulfation). The underlying principles of attrition in these experiments are completely different from bubble-induced or nozzle-induced attrition and can therefore not be compared with our findings.

Particle attrition in fluid-bed systems was first studied to characterize catalysts for fluid-cracking systems, and to rank different candidate catalysts towards their attrition behavior [10–12].

Vaux and Keairns [5] tested several sources of attrition, i.e. particle heating, calcination, sulfatation, low and high velocity impacts, and their importance to particle size reduction through wear, fracture, decrepitation, abrasion, splitting, shattering, chipping and disintegration. Their extensive work concluded that high and low velocity impacts needed to be distinguished. Low-velocity impact (bubbling bed attrition) has been shown to be less important than other sources. The rate of fines formation (kg/kg s) appears to be proportional to

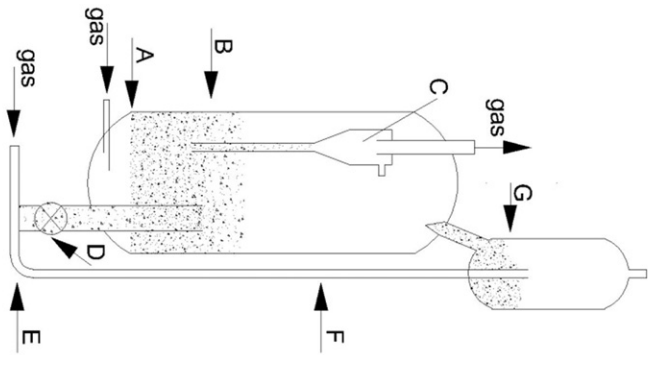

Fig. 2. Fluidized bed zones where attrition/erosion can occur. A: at the orifice plate. B: in the fluidized bed. C: in cyclones. D: at the entrance of rotating locks. E: in bends. F: at the walls of transport pipes. G: in any equipment where particles fall down.