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Dynamic forces on a horizontal slat immersed in a fluidized bed of fine particles

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ABSTRACT

Forces on a single horizontal slat immersed in a fluidized bed of Geldart A particles were investigated for the purpose of providing useful design guidelines for long-period reliability of horizontal baffles in industrial reactors. The characteristics of slat forces in the fluidized and de-fluidized states of a reactor were measured using adhered strain gauges. The main parameters influencing these characteristics were superficial gas velocity, installation height, inclination angle, and method of slat installation. The experimental results show that the measured force on the slat in the fluidized state is highly fluctuating, but its root-mean-square is usually significantly lower than for the de-fluidized state, especially at the bottom of the bed. The effects of various operating and structural parameters were determined. Critical locations and operating conditions under high load are indicated and warrant more attention in structural design of horizontal baffles.

1. Introduction

For their high efficiencies in mass and heat transfer and uniform temperature distribution, fluidized reactors are widely used in many important industrial processes, such as petroleum refining and chemical synthesis (Davidson et al., 1985; Kunii and Levenspiel, 1991). In these reactors, fine Geldart A particles and bubbling/turbulent regimes are often employed. However, the presence of bubbles promotes gas channeling, non-uniform gas distribution, and bubble coalescence, and hence results in poor gas–solids contact in industrial fluidized reactors. Another problem is strong gas/solids back-mixing induced by movement of bubbles, which contributes to a considerable non-uniform distribution in residence time of either gas or solids in the bed. For a specified fluidized reactor, the resulting consequences may be low conversion or poor product selectivity, both incurring low profitability.

To solve these problems, researchers found that adding baffles or internals in fluidized bed is an effective way to split bubbles and improve the lateral distribution of bubbles to enhance gas–solids contact while suppressing gas/solids back-mixing to optimize residence time distributions (Dutta and Suciu, 1992; Harrison and Grace, 1971; Jin et al., 2003, 1986; Kwauk, 1996; Rall and Demulder, 2000; Rall and Wichita, 2001; Zhang et al., 2009, 2008). Of the various types of baffles, those with inclined slats, e.g., the louver baffle (Kwauk, 1996; Zhang et al., 2009, 2008), the ridge baffle proposed by Jin et al. (1986), and KFBE packing (Koch–Glitsch) (Rall and Demulder, 2000; Rall and Wichita, 2001) were reported to be more effective in breaking up bubbles and suppressing solids back-mixing in fluidized beds. They are often the choice in many industrial fluidized reactors.

However, as chemical reactors are often required to operate continuously for years, forces arising from bubble and solids motions during operation may result in the vibration, material fatigue over time, and finally failure of the immersed baffles or their supports. If not designed properly, the baffles may deform excessively or even be destroyed because of their weight or squeezing of static material during a de-fluidized state, which is more probable in an industrial reactor with a large bed diameter or high bed level. Here, squeezing means the solids material above the internals presses them downward due to gravity. To mitigate such problems, details of the forces acting on the baffles must be gathered to implement a better engineering design.

However, few studies have been conducted in this aspect. Hosny (1982) was one of the early researchers who has performed a systematical study of the characteristics of the dynamic forces on horizontal tubes immersed in a fluidized bed with a rectangular cross section of 215 × 200 mm. Horizontal tubes are widely used as heat exchange tubes

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Nomenclature

a	Width of the test slat (m)
b	Thickness of the test slat (m)
f	Frequency (Hz)
F_{45}	Fraction of fine particles with diameter less than 45 μm (%)
h	The distance of slat installed away the bottom gas distributor (m)
H_0	Static bed height (m)
L	Length of the test slat (m)
M	Moment of the beam under an uniform load (N m)
PSD	Power spectral density (MPa^2/Hz or Pa^2/Hz)
q	An upward uniform load (N/m^2)
q_{AVG}	The effective load density in de-fluidized bed (N/m^2)
q_{RMS}	The effective load density in fluidized bed (N/m^2)
S_p	Standard deviation of the pressure fluctuation (kPa)
t	Time (s)
u_c	Onset velocity of the turbulent flow regime (m/s)
u_f	Superficial gas velocity (m/s)
u_{mf}	Minimum fluidization velocity (m/s)
W	Section modulus of the test slat (m^3)
x	The distance to the left fixed end (m)

Greek letters

θ	Inclination angle of the test slat (°)
σ	Measured transient stress on the surface of the test slat (MPa)
$\sigma_{RMS,i}$	RMS stresses measured at different measuring points (MPa)
$\hat{\sigma}_i$	Calculated stresses at different measuring points (MPa)
σ_i	Measured stress at different time (MPa)
σ_{RMS}	RMS value of measured stress signal in a period (MPa)
φ	The sum of the square of the difference between nine measured RMS stresses and the absolute values of nine calculated stresses at the same positions (MPa^2)

in fluidized boilers. The effects of superficial gas velocity, static bed height, particle size and density, tube shape, tube array configuration on forces exerted on the tubes of various diameters were tested. The magnitude of the forces is strongly influenced by superficial gas velocity, slightly dependent on particle size, and moderately affected by bed depth and particle density. The horizontal force components have significantly lower magnitude than the vertical force components. The intensity of the force exerted on a single tube in a tube bundle is found to be reduced significantly, which was also proved by a later study by Nagahashi et al. (2008). Hosny and Grace (1984) also found that the upstream (lowermost) tubes in a bundle experienced the largest root-mean-square (RMS) forces, while tubes in the top row encountered the smallest RMS forces.

Kennedy et al. (1981) and Donovan (1980) also measured forces on horizontal 50-mm-OD tubes of various lengths immersed in fluidized beds of different sizes. The dynamic forces were obtained by attaching strain-gauge load cells on the surface of each test tube. Their experimental results showed that the magnitude of the forces depended roughly linearly with tube length.

To understand the mechanism of bubble motion and transient forces, Nagahashi et al. (1998) measured the transient force on a single horizontal tube from a single injected bubble. The pressure profiles around the tube and the movement of the bubble were also measured by pressure transducers and recorded synchronously with a video camera. By comparing the transient force signal and the recorded bubble movement, they identified the key mechanisms relating to the forces buffeting tubes. The force from the impact of the bubble wake was found to be considerably higher than that caused by the gas pressure field. Levy et al. (1992a,b), also found similar results in their experiment.

Recently, Nagahashi et al. (2013) also studied the dynamic forces on horizontal tubes of non-circular cross-section in a two-dimensional fluidized bed. The effects of tube cross-sectional shape were identified by image analysis similar to Nagahashi et al. (1998). The upward impulse force by wake particles, downward friction, and wake-shedding were found to be the predominant factors contributing to the force.

Following these previous studies, a good understanding of the mechanism of forces on tubes caused by bubble motions has been obtained. However, most of the research effort was devoted to the dynamic forces on horizontal tubes in bubbling fluidized beds of Geldart B particles, and concerned mainly the heat exchange tubes found in most fluidized boilers. Little work was done on the baffles (usually inclined slats) in fluidized reactors with Geldart A particles typically operating in the high-velocity turbulent regime. As fluidized beds with different Geldart groups of particles present distinct hydrodynamic behavior (Davidson et al., 1985; Kunii and Levenspiel, 1991) and the effects of baffle shape on bed hydrodynamics are also very significant (Dutta and Suciu, 1992; Harrison and Grace, 1971; Zhang et al., 2009, 2008), the understanding obtained from previous studies on forces acting on the tube is insufficient and incomplete in guiding the design of baffles in these fluidized chemical reactors.

In our study, we assembled a large cold-model fluidized bed of fluid catalytic cracking (FCC) particles (typical Geldart A particles). A single horizontal slat made of stainless steel, representing the most important component of typical baffles used in fluidized chemical reactors, was employed to study the dynamic forces acting on it in both fluidized and de-fluidized states. The main parameters varied in this study were superficial gas velocity, installation height, inclination angle and installation method of the slat. The objective of this study was to establish a fundamental understanding of the force characteristics acting on a single slat to build a strong knowledge base for better structural engineering design of horizontal baffles in industrial fluidized reactors.

2. Experiment

2.1. *Experimental unit*

Experiments were performed in a fluidized column of cross-section 300 × 300 mm and height 5 m (Fig. 1). The column walls were made of transparent plexiglass so as to observe the inner gas–solids flow. Fluidizing air was supplied into the bed using a Roots blower. A regulating valve controlled the superficial gas velocity in the bed, which was monitored using a digital turbine flowmeter installed in the pipeline. After passing through a plenum chamber, air was uniformly distributed into the bed by a perforated plate distributor of open-area ratio of 0.6%. A steel wire screen (200 mesh) covered the distributor from above to prevent fine particles from dropping into the plenum chamber. Particles entrained in the gas leaving the fluidized bed were recovered using two high-efficiency cyclones installed in series. The collected particles were returned to the dense bed via their diplegs. The total separation efficiency of the two cyclones was nearly 99%, which helped maintain the solids inventory and their particle size distribution in the bed unchanged over long periods. Meanwhile, particles escaping