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Forces on an immersed horizontal slat during starting up a fluidized bed

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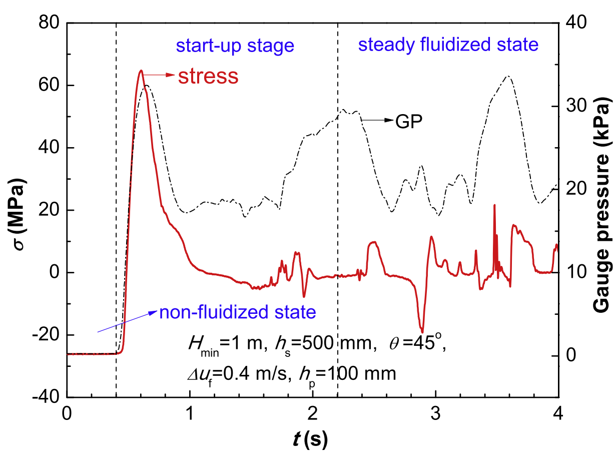
HIGHLIGHTS

- Forces on the slat were systematically measured during starting-up a fluidized bed.
- Critical locations and operating conditions with high load were determined.
- Useful measures to alleviate the strong force are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Forces acting on a horizontal slat immersed in a fluidized bed during its start-up stage were investigated systematically. Both stress and pressure signals were measured by using strain gauges and pressure transducers to describe the forces and their relationship with gas-solids hydrodynamics. The main influencing parameters are the increment of superficial gas velocity, installation height, inclination angle, static bed height, and installation method of the slat. The experimental results indicated that there is a dangerous upward impulse with a high peak and a long duration in the measured stress signal during starting up a fluidized bed. The effects of various operating and structural parameters on the forces acting on the test slat were elucidated in detail. Effective measures to alleviate the forces and critical conditions where the strength of internals needs to be re-enforced are proposed. The obtained knowledge is helpful to engineering design to ensure the safety of immersed internals in fluidized bed reactors.

1. Introduction

Fluidized bed reactors are widely applied in many important industries, such as chemical synthesis, petroleum refining, power generation, food processing and so forth (Davidson et al., 1985; Kunii and Levenspiel, 1991). Baffles made of multiple slats are often installed in these reactors to break up bubbles, promote lateral bubble distribution and hence enhance gas-solids contact. Another important function of these baffles is to suppress gas/-solids back-mixing and change their 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., 2008, 2009). The ultimate objective

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Nomenclature

a	width of test slat (m)
b	thickness of test slat (m)
F	force acting on the free end of test slat (N)
h_s	position of test slat installed from the bottom distributor (m)
h_p	position of pressure tap located from the bottom distributor (m)
H_f	bed expansion height in steady fluidized state (m)
H_{min}	static bed height (m)
H_{max}	maximum bed expansion height during start-up stage (m)
L	length of test slat (m)
M	bending moment (N·m)
q	upward uniform load density (N/m^2)
q_e	effective load density transformed from measured stress of the slat (N/m^2)
S	area of the test slat surface (m^2)
S_{hp}	horizontal projected area of the test slat surface (m^2)
t	time (s)
u_f	superficial gas velocity (m/s)
W	section modulus of the test slat (m^3)
x	distance from the left fixed end (m)

Greek symbols

Δu_f	increment of superficial gas velocity (m/s)
φ	sum of square difference between measured and calculated stresses (MPa^2)
θ	inclination angle of test slat
σ	transient stress signals of test slat measured along length direction (MPa)
σ_{max}	peak of measured stress impulses (MPa)
σ_i	peak of measured stress impulses at five measuring points (MPa)
$\hat{\sigma}_i$	calculated stresses at five measuring points (MPa)
$\hat{\sigma}_{(x)}$	stress profile along length direction of test slat (MPa)

Abbreviations

DP	differential pressure
GP	gauge pressure

is to achieve higher conversion, better product selectivity and higher profitability. There have been numerous research efforts on baffle's effects on bed hydrodynamics and reactor performance as summarized by the reviews of Harrison and Grace (1971) and Jin et al. (2003).

On the other hand, as industrial fluidized bed reactors often require operating continuously for years, the long-period safety and reliability of immersed baffles in bed is also a prominent concern, especially for industrial community. Therefore, detailed information on forces acting on baffles under different operating conditions is necessary for optimized design of the structure and strength of these baffles and other immersed internals.

In this field, a large number of previous publications have been focused on the force characteristics on tubes immersed in steady-state operation (Donovan, 1980; Grace and Hosny, 1985; Hosny, 1982; Hosny and Grace, 1984; Kennedy et al., 1981; Kono et al., 1990; Kumar, 2016; Levy et al., 1992a,b; Nagahashi et al., 1998, 2008, 2013; Turner and Irving, 1983). An important industrial background is the wide applications of immersed heat tubes in fluidized bed boilers. Hosny (1982), Kennedy et al. (1981) and Nagahashi et al. (2008) conducted a series of systematic studies on the effects of various operating and structural parameters (e.g. superficial gas velocity, bed height, particle properties, tube shape, and tube array configuration, etc.) on the characteristics of dynamic forces on a horizontal tube or tube bank immersed in bed. They found that the magnitude of the dynamic force is strongly influenced by superficial gas velocity, slightly dependent on particle size, and moderately affected by bed depth and particle density. Compared to a single immersed tube, the force intensity acting on a tube in the interior of the tube bank was found to be reduced significantly. On the other hand, to understand the mechanism of dynamic force on an immersed tube, Nagahashi et al. (1998) and Levy et al. (1992a,b) measured the transient force signal on a single horizontal tube using a single-bubble injection method. Combined with synchronous camera recording in their two-dimensional beds, the key interaction mechanisms between the bubble movement and the buffeting force on the tube could be elucidated more clearly. The impact from wake particles in a rising bubble was found to be the strongest contributor to the dynamic force on immersed tubes. Recently, we also have done some investigations on the dynamic forces on a slat, representing one of the most important components of typical baffles widely used in fluidized bed reactors, immersed in bed in steady fluidized state (Liu et al., 2016, 2017; Wang et al., 2015).

Except for steady fluidized state, force characteristics of baffles in other operating conditions, e.g. non-fluidized state, start-up stage, de-aeration stage during closing a fluidized bed reactor, also need be considered during design of baffle's structure and strength. In our past cold model fluidized bed experiment several years ago, we accidently found that a protective stainless-steel tube of OD 20 mm for an optical fiber probe was bent in a fluidized bed of ID-800 mm during starting up the bed, as we forgot to extract the probe from the bed after the previous experiment. This suggested that a considerably high short-term force on immersed internals may exist during the start-up stage. In fact, fluidized bed reactors often start up directly from a non-fluidized state and then return to a steady fluidized state, e.g. when power-down or blower-stopping accidents happen. If this phenomenon is not considered by designers or protective measures are not adopted by operators to alleviate the possible strong force, potential danger to the immersed baffles or internals may be caused. Some internals may deform excessively or even be destroyed due to the high short-term force, especially in an industrial reactor with a large bed diameter or a high bed level. After that, the fluidized bed reactor may worsen in performance or even have to be shut down for repairs. To our knowledge, there is still no study on the force characteristics acting on immersed internals during this special operating condition. Therefore, it is difficult for designers and operators to avoid this danger.

In this study, we built a large cold model fluidized bed. A single horizontal slat made of stainless steel was employed to investigate the force characteristics during starting up a fluidized bed. The main influencing parameters varied in this study were increment of superficial gas velocity, static bed height, installation height, inclination angle and installation method of the slat. The purpose of this study was to provide basic knowledge of force characteristics and guidelines for structural design of immersed baffles or internals in industrial fluidized bed reactors. Moreover, some effective measures to alleviate the strong force and avoid damages of internals are also expected to be proposed based on the obtained