Powder Technology 256 (2014) 300–309

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Hydrodynamic characterization of a tapered gas–solid bed without a gas distributor

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ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 14 January 2014
Accepted 11 February 2014
Available online 16 February 2014

Keywords:
Tapered bed
Fluidized bed
Spouted bed
Hydrodynamics
Gasifier

ABSTRACT

The tapered fluidized bed (TFB) without a gas distributor has long been used as an atmospheric coal gasifier by taking advantage of its simplicity in configuration and maintenance and also its ease in discharging bottom ash. This study investigated the hydrodynamic characteristics of such a bed fluidizing quartz sand of 156 μm in mean diameter to understand if it enables the fully uniform fluidization of its particle bed. The changes in pressure drop and voidage in the bed were measured under varied conditions. Three flow regimes were identified by gradually increasing the superficial gas velocity through the bed. The gas–solid flow in the bed can be divided vertically into three gross sections of gas convergence, gas diffusion and particle elutriation, and laterally into two zones of annulus and core. Vertically along the bed the shape of the radial voidage profile changed gradually from an "M" shape to a "parabola" by increasing the superficial gas velocity from 0.17 m/s to 0.35 m/s. The axial voidage profile at the bed center showed the "S" shape to distinguish the above-mentioned three vertical sections. These indicated the existence of non-uniformity of particle fluidization in the bed, and changing the arrangement of gas jets into the bed did not fully resolve the problem. The article found also that the major hydrodynamic parameters of the tested TFB using only one layer of gas jet to supply the fluidizing gas could be predicted by modifying their empirical correlations known for the TFB with a gas distributor.

1. Introduction

Tapered fluidized beds (TFBs) are characterized by the capability of treating particles of different sizes and properties due to their velocity gradient existing in the axial direction [1–3], and they can be operated more stably than straight cylindrical or columnar fluidized beds [4]. Because of this, the hydrodynamics of TFBs have received great attention and have been widely studied. The studies in the literature focused mainly on the flow regime transition [4–6] and calculation equations for bed pressure drop and minimum fluidization velocity [7–10]. Peng and Fan [4] studied the fluidization characteristics of liquid–solid TFBs and five flow regimes were identified, the fixed, partially fluidized, fully fluidized, transition and turbulently fluidized regimes. Jing and Hu [5] also observed the fixed, partially fluidized and fluidized beds with the increase of superficial gas velocity for a kind of Geldart D particles in a TFB. They found that the bed cone angle and the particle bed height were the main factors influencing the regime transition and flow hydrodynamics. However, for Geldart A particles, the partially fluidized regime was not found in the TFBs [6]. Sau et al. [7] and Khani [8] proposed models based on dimensionless analysis to predict the minimum fluidization velocity and maximum bed pressure drop for gas–solid TFBs, and they found that the predictions comply well with the experimental values. Maruyama [9] and Sau et al. [10] studied the expansion behavior of TFBs and developed models to predict the bed expansion ratio with reasonable accuracy.

Almost all the TFBs studied in the literature have flat or conical gas distributors [4–14]. Compared with the fluidized bed with a distributor, the bed without a gas distributor can reduce pressure drop loss and avoid the possible jams of the distributor orifices and also the bottom ash discharge port. This is especially useful for treating adhesive materials such as caking coal at certainly high temperatures. In fact, the TFB without a gas distributor has been successfully applied to be the so-called Ende gasifier, an atmospheric fluidized bed gasification technology [15,16]. Fig. 1 shows a schematic process diagram of the gasifier. The primary gasification agent of air (70–80% of total) is introduced into the gasifier through several (usually 6) jetting nozzles located around the tapered bottom touching the cone with angles of about 90° vertically and 10° horizontally. The secondary gasification agent is supplied into the bed through the jetting nozzles on the cylindrical section of the gasifier. More than 30 Ende gasifiers have been deployed in China for commercial operations to make fuel gas or syngas for ammonia synthesis at scales of 300–400 t/d of coal.

As shown in Fig. 1, the fluidized bed without a gas distributor usually uses a few jetting nozzles around the cone bottom of the bed to supply the fluidizing gas, which may result in poor fluidization due to the

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http://dx.doi.org/10.1016/j.powtec.2014.02.037
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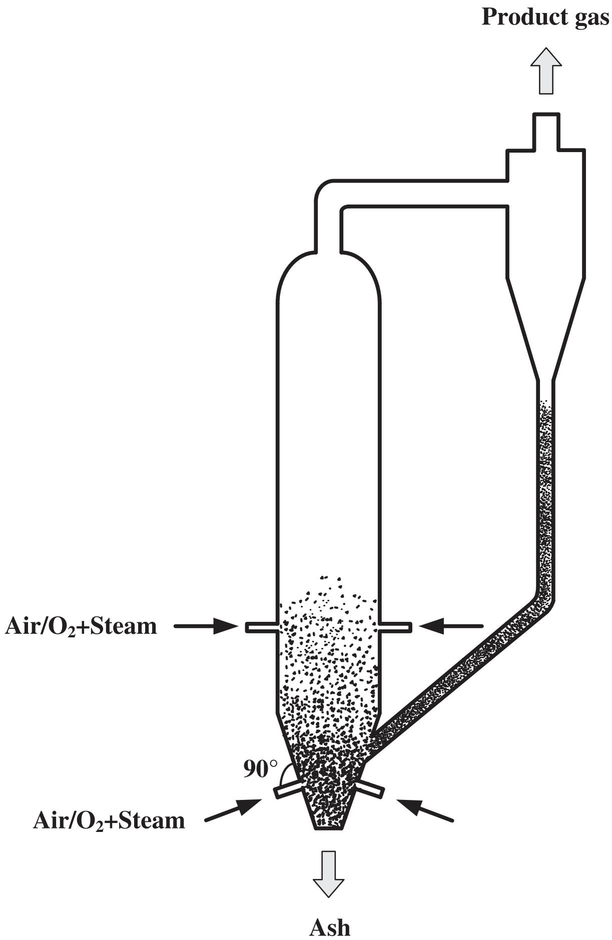

Fig. 1. A schematic process diagram of the Ende gasifier.

uneven gas distribution at the bottom of the bed. Therefore, it is necessary to clarify the hydrodynamic characteristics including regimes, structures, fluidization and spacial profiles in this kind of beds and also to explore the possible effective approaches to reduce the uneven gas distribution for obtaining the desired full fluidization of particles as in the normal fluidized bed with a gas distributor. These are in fact never studied before, according to our knowledge of the open literature. The developer of the Ender gasifier did not importantly view the fluidization characteristics in the bed, but the technology itself is in fact unable to treat the coal with even very low caking propensity. The relatively poor coal adaptability of the Ende gasifier is possibly caused by the poor fluidization of particles in the gasifier. We have had also an intention to extend the application of the TFB gasifier without a gas distributor to caking coal [17].

In this study, a laboratory cold apparatus of such a TFB was consequently built and tested to understand its major hydrodynamics including flow regime transition, gas distribution and particle fluidization characteristics in the bed. Efforts were also made to optimize the operation and gas jetting deployment for achieving the possible uniform fluidization of particles inside the bed. This study is to provide the necessary fundamental data needed for the further development of the TFB reactor for various applications such as coal gasification.

2. Experimental

All the experiments were carried out at atmospheric pressure and room temperature. Quartz sands with a Sauter diameter of 156 μm and a particle density of 2600 kg/m^3 were used as the bed material, and air was used as the fluidizing gas. The sphericity of the sand was 0.76 and their voidage at loosely packing state was 0.5 (for sand particles in a normal cylindrical column after fluidizing them for several minutes and then stopping the fluidization).

The experimental apparatus, whose main body is made of transparent plexiglass with the thickness of 10 mm, is illustrated in Fig. 2. Two layers of plexiglass nozzles from which the air was introduced into the bed were located horizontally around the conical part of the bed. The axial distance between the two layers of nozzles was 500 mm and the first layer of nozzles was at a height of 200 mm above the bed bottom. The diameter of the nozzles was 25 mm. Before each measurement, the sand was first put into the bed, and then the injected air controlled by rotameters passed through the gas nozzles and entered the particle bed. The stable flow state was usually obtained after several minutes of gas injection.

To measure the pressure drop across the bed, two measuring ports were installed on the wall of the TFB. One port was located slightly above the air nozzles and the other was located just above the surface of the particle bed. The two ports were connected through their pressure probes to a differential pressure transducer to measure the pressure drop across the bed. A small piece of steel screen (325 meshes) was filled into the tip of each pressure probe to prevent the particles from entering the pressure measurement line. The data of air flow rate and the differential pressure transducers were all sampled using a computer.

The bed voidage was measured with an optic fiber probe system (PV6) made by the Institute of Process Engineering, Chinese Academy of Sciences. A detailed description of this system can be found in the literature [18]. The optic fiber probe with an external diameter of 6 mm was inserted horizontally into the bed through the measurement ports at various bed heights. The sampling frequency was 500 Hz and each measurement lasted for about 260 s. At each bed height, the ports used for the optic fiber probes were located at two different positions on the bed, one directly above the gas jetting nozzles (see position I in Fig. 2), and the other between two neighboring nozzles (position II).

In this study, we first studied the hydrodynamics of the TFB without a gas distributor using only the lower layer of nozzles to introduce air into the bed while the upper layer of nozzles were sealed. Then, the tests adopting the two layers of nozzles were also conducted to improve the fluidization quality of the bed. In this article, the superficial gas velocity u_0 and initial bed height H_i in the TFB was based on the cross section of the bed at the height mounting the first layer of the gas nozzles. All the experiments were repeated three times for the pressure drop and voidage measurements and their respective average values obtained were adopted in the analyses of this article.

3. Experimental observations

3.1. Flow regimes and regions with one layer of nozzles

Fig. 3 shows the typical dependence of the pressure drop across the bed, ΔP, on the superficial gas velocity u_0 for the case of air feed only from the lower layer of nozzles. With increasing u_0, the dependence curve in Fig. 3 can be divided into three regions to typify three different flow regimes: the fixed bed regime, partially fluidized regime and steadily fluidized regime (meaning not fully fluidized). The flow or fluidization characteristics of each of these three stages are described below:

(1) O → A stage: the pressure drop ΔP rises with u_0 and the particle bed height remains unchanged. At point A, ΔP reaches its maximal value, as shown in Fig. 3. This phenomenon is also observed for the liquid–solid TFB and gas–solid TFB with a gas distributor [4,5]. The corresponding flow regime is thus a fixed bed and the u_0 at point A is termed the minimum partial fluidization velocity u_{mpf}.