Particuology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Particuology

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

Minimum spouting velocity of flat-base spouted fluid bed

Esmail R. Monazam[b], Ronald W. Breault[a,*], Justin Weber[a], Ky Layfield[b]

[a] National Energy Technology Laboratory, U. S. Department of Energy, 3610 Collins Ferry Rd., Morgantown, WV 26507-0880, USA
[b] REM Engineering Services, PLLC, 3537 Collins Ferry Rd., Morgantown, WV 26505, USA

A R T I C L E I N F O

Article history:
Received 5 October 2016
Received in revised form 16 February 2017
Accepted 23 February 2017
Available online xxx

Keywords:
Spouted bed
Spout-fluidized bed
Minimum spouting velocity
Flat-bottom spouted bed

A B S T R A C T

Experiments were performed on spout characteristics of a cylindrical spout-fluidized bed (I.D. = 10 cm) with different static heights and two materials (Al_2O_3 and high density polyethylene). Results of minimum spouting velocity obtained in this study were compared with reported correlations for both spouted and spout-fluidized beds. Considerable discrepancies were found between the values obtained using different model equations as well as with respect to experimental results. Based on the Mathur–Gishler correlation, a new correlation is proposed for calculating the minimum spouting velocity that introduces the ratio U/U_{mf}. It was found that the minimum spouting velocity decreases with increasing fluidizing gas velocity (U/U_{mf}). The pressure drop at the point of minimum spouting velocity is also correlated using this dimensionless group and is presented in this work. This investigation demonstrates that the use of correlations reported in the literature that focus primarily on conical bottom spouted beds are not applicable to flat-bottom spouted and spout-fluidized beds.

Published by Elsevier B.V. on behalf of Chinese Society of Particuology and Institute of Process Engineering, Chinese Academy of Sciences.

Introduction

The United States Department of Energy has initiated a CO_2-capture program for reducing emissions by removing and sequestering 90% of those emissions produced at future coal power plants. The goal of this project is to accomplish emission reduction by limiting the increase in cost of electricity by less than 35% for post-combustion and oxy-combustion, coal-fired power plants. There are several options to remove CO_2 from existing coal-fired power plants including membranes, liquid and solid sorbents, and oxy-combustion. The use of membranes and sorbents require a large amount of energy to remove CO_2 from the diluted process gas and into a separate stream for sequestration. The oxy-combustion process is a promising technology that uses the product of the combustion, which is a binary mixture of CO_2 and water (H_2O), and separates the CO_2 by condensing the water vapor (Anheden & Svedberg, 1998). The issue with this approach is that cost and performance is primarily dependent on the capability of the air-separation unit to extract oxygen.

Chemical looping combustion (CLC) is an alternative process for the combustion of fossil fuels, while providing complete CO_2 capture (Corbella, De Diego, García-Labiano, Adánez, & Palacios, 2005; Corbella, De Diego, García-Labiano, Adánez, & Palacios, 2006; Mattisson, Järdnäs, & Lyngfelt, 2003; Mattisson, Johansson, & Lyngfelt, 2004). The process now commonly known as chemical looping was first developed by Richter and Knoche (1983), the proposal being that the fuel must react with an oxygen carrier in a flameless combustion. However, the idea of using a metal oxide as an oxygen carrier was first proposed in 1956 by Lewis and Gilliland (1954) as a method to produce pure CO_2. In chemical looping, the oxygen in the oxygen carrier completes the combustion of the carbonaceous fuel in the fuel reactor and then is re-oxidized or regenerated back into the metal oxide form by air in an air reactor. This is then recirculated back into the fuel reactor to complete the loop. With this method, the fuel and air are not mixed and the products of fuel oxidation, CO_2 and water, are able to escape the system undiluted by excess air and a large volume of CO_2. A pure stream of CO_2 is produced by condensing and separating the water from the flue gas. Therefore, CLC produces a binary mixture of CO_2 and H_2O without dependence on energy and expensive costs from the separation of flue gas.

The development of CLC for gaseous fuels has undergone significant improvement in the last decade; however, the use of direct coal CLC is a novel approach that brings issues such as the accumulation of ash byproducts during combustion. Various options have been proposed to mitigate ash-related problems to allow for longer combustion periods such as the use of alternative bed materials, injecting mineral additives during combustion, pretreatment

* Corresponding author.
E-mail address: ronald.breault@netl.doe.gov (R.W. Breault).

http://dx.doi.org/10.1016/j.partic.2017.02.008
1674-2001/Published by Elsevier B.V. on behalf of Chinese Society of Particuology and Institute of Process Engineering, Chinese Academy of Sciences.

Nomenclature

Ar	Archimedes number, $Ar = \frac{d_p^3 \rho_g(\rho_s - \rho_g)g}{\mu^2}$
d_j	inlet jet diameter (m)
d_p	mean particle diameter (m)
D	bed diameter (m)
g	acceleration due to gravity (m/s^2)
H	static height (m)
Re_{ms}	minimum spouting Reynolds number
U_g	superficial gas velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
U_{ms}	minimum spouting velocity (m/s)

Greek symbols

μ	gas viscosity (g/(cm·s))
ρ_b	bed density (g/cm^3)
ρ_g	gas density (g/cm^3)
ρ_s	particle density (g/cm^3)
ΔP_{ms}	bed pressure drop across the particles inside the spouted bed at minimum spouting condition (kPa)

of coal, or using blended coal (Vuthaluru & Zhang, 2001). Each of these options however requires the extraction of both ash and oxygen carrier from the system which requires fresh oxygen carriers to replace the contaminated material. Fluidization is the commonly used technique for gas–solid contact in the fuel reactor, where the application favors fine particles to ensure proper operation. However, the authors propose the use of a spouted bed as an alternative to a fluidized bed for the fuel reactor.

Spouted-bed technology use has significantly increased in the context of drying and coating (Briongos & Guardiola, 2005; da Rosa & dos Santos Rocha, 2010; Kutsakova, 2004; Salam & Bhattacharya, 2006), pyrolysis (Alvarez et al., 2015; Amutio et al., 2012), combustion (Banerjee & Agarwal, 2015; Wang, Kong, Liu, & Xiao, 2013), and gasification (Lopez, Erkiaga, Amutio, Bilbao, & Olazar, 2015; McCullough, van Eyk, Ashman, & Mullinger, 2015). Mathur and Epstein (1974) also summarized the various industrial applications in the early decades. A spouted bed consists of a concentrated stream of the fluidization gas from the gas inlet that creates a jet that penetrates the bed material and creates a countercurrent flow of the material. The cycle consists of the bed material flowing from the top of the bed surface down to the base through the annulus where once the particles reach the bottom of the bed they are consumed into the gas stream of the spout and carried to the surface of the bed where the spout ejects them into the freeboard creating a fountain of flowing particles. The particles rain down from the fountain and fall on to the top surface of the bed where the process is repeated. The boundary between the spout and outer annulus creates a shearing effect that is highly efficient in ensuring full contact between the gas and solids (Kunii & Levenspiel, 1991). Hence, a spouted bed has three different regions: the annulus, the spout, and the fountain (Bacelos & Freire, 2008; Olazar, San José, Izquierdo, de Salazar, & Bilbao, 2001). There are at least four widely used spouted-bed configurations: flat-base cylindrical, cone-base cylindrical, conical, and dilute jet. In some cases, a cylindrical draft tube is inserted in the center of the bed to stabilize the interface between the upward- and downward-moving solids (Hattori, Ito, Onezawa, Yamada, & Yanai, 2004; Zhao, Yao, & Li, 2006). This enhances the separation between the upward and downward flow zones and increases the overall circulation rate.

It has been found that spouting is stable under certain conditions of bed geometry and particle size. Becker (1961) noted that for a given bed height and diameter, there is a limit to inlet diameter beyond which spouting was no longer possible. The critical point was defined in terms of the ratio of bed to inlet diameters of about 3. Pallai, Nemeth, and Aradi (1984) reported the upper limit of this ratio to be about 22.5 and optimum values in the range of 6–10. Pallai et al. (1984) also indicated that for cylindrical bed diameters ranging from 0.06 to 0.58 m, the optimum ratio of the bed diameter to particle size is between 25 and 200. Nemeth, Pallai, and Aradi (1983) reported the ratio of gas inlet jet to particle diameter of 3–30 for good spouting. Mathur and Epstein (1974) noted the practical range of 2–6 for the height-to-diameter ratio for conical-spouting bed using coarse granular materials of greater than 1 mm.

A variant of the spouted bed is the spout-fluidized bed, which has s similar operation but different characteristics. Configured like a spouted bed, this variant has a discrete orifice distributor plate located in the bubbling fluidized bed. Hence, not only is a concentrated gas stream in the spout present but also gas from the distributor plate being used. The material flow of both beds is the same with an inner jet stream and outer annulus. However, the fluidization gas from the discrete orifices can cause a reduction in the fountains height when a high gas flow rate is used. The reduced fountain height is caused by bubbles coalescing near the surface of the bed from the fluidization gas and affecting the direction of the gas for the jet stream as it interacts with the bubbles. A spout-fluidized bed offers a higher level of interaction between gas and solids but reduces the spout's capability to eject particles into the freeboard. Fig. 1 contrasts the physical differences between these two bed types.

The spouted bed allows for the use of dense particles from Geldard's group D classification, i.e., those that are larger than 600 μm in diameter. These coarse particles are deemed as spoutable and are effectively fluidized when used properly (Geldart, 1986). Spoutable particles include coal that requires less sizing preparation and large diameter. Both spouted and spout-fluidized beds have proved favorable in coal combustion due to their capability to prevent agglomeration or sintering of the bed materials (Lim et al., 1988; Vuthaluru & Zhang, 2001; Ye, 1988). For differences in application between these two beds, temperatures across the bed are generally more uniform in the spout-fluidized configuration compared with the spouted bed as warranted by the auxiliary gas flow, which reduces occurrences within the bed of concentrated high-temperature zones. The belief is that a spouted or spout-fluidized bed allows for the best combination of benefits in the combustion of

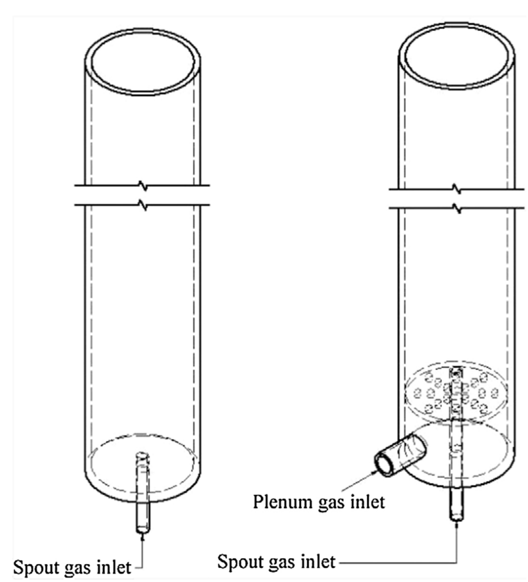

Fig. 1. Spouted (left) and spout-fluidized (right) beds.

Please cite this article in press as: Monazam, E. R., et al. Minimum spouting velocity of flat-base spouted fluid bed. *Particuology* (2017), http://dx.doi.org/10.1016/j.partic.2017.02.008