Improvement of Solid-Gas Interaction in Fluidized Bed Systems via Secondary Air-Injection

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Abstract. Since the invention of fluidized bed systems to augment chemical reactions, numerous innovations were introduced to the system. These innovations result-in substantial improvement to the overall efficiency apart from resulting the fluidized bed system to become more compact. One of the innovations were the introducing of secondary air inside the bed so that a secondary motion in lateral direction can increase the amount of solid-gas interaction. This paper reviews various techniques proposed by researchers in providing secondary air inside the fluidized bed system. In general, four techniques were common in which the bed was named after: vortexing bed, cyclonic bed, rotating bed and swirling bed. Though resemble similarity, each of these beds were unique and comes with different advantageous. In conclusion, a fluidized bed system can be improved by the secondary motion in the bed which provides opportunities for further innovations.

1 Introduction

Fluidization is the operation by which solid particles are transformed into fluid-like state through suspension in a gas or liquid. This method of contacting between solid and fluid has some unusual characteristics, and fluidization engineering puts them in to good use [1]. The basic mechanism of a fluidized bed can be seen simply as fluid percolation through particle interstices, in which particles begin to exhibit fluid-like characteristics upon experiencing sufficient drag force by the fluid.

Since the last 80 years, fluidized bed technology has served many industries involving solid – fluid contact due to their apparent advantages such as excellent mixing and homogeneity in heat and mass transfer. Today, fluidized bed systems are widely used in processes such as combustion and gasification of solid fuels, biomass processing, heat recovery, drying of particles, particle heating, oxidation of metal ores, metal surface treatments and catalytic and thermal cracking. The system has made substantial technological advancements ever since and become mature. Nevertheless, the energy crisis and growing industrial needs have motivated continuous initiatives to further improve the existing

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fluidized bed technology. Different designs of the system components, particularly the distributor, and their effect on bed performance are some of the examples.

Among the well-established variants in fluidized bed systems, such as the centrifugal fluidized bed, tapered fluidized bed, spouted bed, rotating bed and vibrating bed, there is a group of fluidized beds which operate based on swirling (or vortexing or cyclonic) principles. Although the terms swirling, vortexing and cyclonic may seem to address the same system, there are several salient features distinguishing them from each other.

2 Fluidized bed distributor

In a fluidized bed system, the distributor may be regarded as the 'heart' of the system. A good design of gas distributors is vital to ensure satisfactory performance of the fluidized bed system as well as success in industrial applications which adopt the fluidization technique. The large numbers of publications on the distributor design since the last three decades prove that there still are unresolved questions in gas distributor designs in actual operation. According to Geldart and Baeyens [2], some of the basic requirements of a gas distributor are uniform distribution of gas into the fluidized bed, operation at as low pressure drop as possible to minimize power consumption, sufficient strength to withstand both thermal and mechanical stresses, prevention of particle drainage, reduction in particle attrition and prevention of plate erosion. These requirements may be contradictory and their relative importance depends on the process needs.

Although distributors with low pressure drop are preferred to reduce energy consumption during processing, it should be noted that distributors having too low pressure drops may result in poor fluidization. This is due to more flow of process gas taking place at the zone with lowest flow resistance. As a result, the bed may be permanently defluidized, whilst in other parts semi-permanent spouts or channels may be occurring [2]. Therefore, the distributor pressure drop has to be large enough to overcome the small local pressure disturbances of the fluidized bed.

Many early researchers proposed a ratio between distributor pressure drop and bed pressure drop ($\Delta P_d/\Delta P_b$) as design guidelines. Agarwal et al. [3] proposed that ΔP_d should be approximately 10% of the bed pressure drop and never less than about 3500 Pa (350 mmH₂O), while Siegel [4] proposed a minimum value for $\Delta P_d/\Delta P_b$ ranging from 12% to 24%. In more recent industrial designs by Gupta and Sathiyamoorthy [5] and Mujumdar [6], pressure drop ratio values of not less than 25% to 50% have been found successful. In line with the rapid progress in this area over the years, a large variety of distributors has been studied and reported.

Investigation on the influence of various distributor designs, namely perforated plate, punched plate and Dutch weave mesh on fluidized bed dryer hydrodynamics were carried out by Wormsbecker et al. [7] and Wormsbecker and Pugsley [8]. Particles in the transition region between B and A (according to Geldart's classification) were tested at various bed loadings and superficial velocities. The distributors were assessed in terms of drying kinetics and pressure fluctuations. The authors found that the punched plate has the best performance as a result of lateral mixing inside the bed, due to swirling flow of fluidizing air. This swirling flow was generated by the horizontal gas jets from the hooded openings of the punched plate.

The effect of air distributor on fluidization hydrodynamics was also studied by Son et al. [9] and Ciesielczyk [10] for large particles. The former conducted experimental work using perforated plate distributors with five different fractions of open area, ranging from 0.9% to 3.7% using 1 mm glass beads as bed material, while the latter proposed a novel distributor consisting of a perforated grate with conical plenum with a solid cone at the bottom for fluidizing various biomass chunks (equivalent diameter ranging from 6.6 mm to 9.2 mm).

Both authors plotted the pressure-velocity curves and concluded successful fluidization though they reported different regimes of operation.

The distributor's influence on the uniformity of fluidization and selection of the aspect ratio at the critical fluidization quality was reported by Sathiyamoorthy and Horio [11]. The authors conducted experiments on two types of multi-orifice distributor with three bed materials having size distribution between 70 – 161 μm and proposed a model equation for predicting critical $\Delta P_d / \Delta P_b$ ratio. The authors claimed that the aspect ratio values were important in selecting a distributor and operating velocity for shallow beds.

Apart from the stationary distributors as mentioned above, Sobrino et al. [12] proposed a rotating distributor with the aim to improve solid mixing as well as achieving fluidization for a shallow bed. The authors tested Geldart B silica sand with various bed heights on a perforated plate distributor with only 1% open area ratio. With the increase of rotational speed of the distributor, the authors reported a decrease in minimum fluidization velocity while the fluidization quality was left unaffected. Perhaps due to the complicated design, the authors discontinued the study and later published their findings on the effect of perforated and bubble-cap distributor on turbulent fluidized bed [13].

Recently, Aworinde et al. [14] proposed a novel gas distributor plate with many upward-facing nozzles incorporated with removable helical coils. Their aim was to swirl the fluidizing gas prior entering the bed. They've conducted experiments using magnetic resonance imaging and concluded that the swirling flow induced by the helical coils significantly improved the bed's fluidization quality despite some increase in the distributor pressure drop.

First patented by Dodson [15] and commercialized by Torftech Ltd since the 1980's, the Torbed® reactor (acronym from Toroidal Bed), consists of angled blades in an annular form at the reactor bottom. When a process gas stream is forced to pass through openings of the blades, the pressure head is converted in the blade array to a velocity head. The resultant high velocity jets keep the bed particles in suspension and rotating toroidally [16].

3 Vortexing/cyclonic/rotating/swirling beds

As fluidized bed systems gained popularity for various industrial applications, the amount of research work also steadily increased to further improve its performance. One of the aspects that has been given particular attention is the lateral mixing inside the bed. These resulted in various innovations to the existing beds, such as introducing secondary air injection at the freeboard of the bed, modifications of the bed geometry (such as the tapered bed and conical bed), utilization of mechanical agitation or stirrer inside the bed apart from introducing various types of distributors. This review addresses some of these efforts but limits its discussion to the fluidized bed systems which resemble the swirling beds. While the terms 'swirling', 'vortexing', 'cyclonic' and 'rotating' indicate a similarity, there are some fundamental differences between them which distinguishes their hydrodynamic characteristics.

3.1 Vortexing fluidized beds

The vortexing fluidized bed was first patented by Sowards [17] in 1977. This system is generally designed as a cylindrical chamber with significant height-to-diameter ratio, with a combination of conventional fluidized bed (in the bottom part of the reactor) with vortexing gas-solid flow in its freeboard [18-22]. The latter is achieved by injecting secondary air tangentially through nozzles, with the aim of increasing the residence time of both gas and solid in the freeboard while reducing elutriation of fine particle from the fluidized bed. The

flow rate of the secondary air in vortexing beds is usually a significant fraction of the primary air fed from the bottom of the bed.

3.2 Cyclonic fluidized beds

Cyclonic fluidized beds usually have moderate height-to-diameter ratio, typically 2.5 - 3.0 [23]. This bed possesses intricate hydrodynamics where the primary air enters the bed tangentially from the top while the secondary air enters from the bottom [24]. Vortex rings are employed to avoid large solids from ascending with secondary air from the bottom as well as dividing the bed into upper and lower parts. However, the authors reported the presence of bed agglomeration due the formation of char during combustion and hence introduced stirring blades at the bed distributor as a countermeasure [25] apart from carrying the combustion study without inert particles [26].

3.3 Rotating fluidized beds

Unlike both types of fluidized bed mentioned above, the rotating fluidized bed actually fluidizes the bed via generating a high centrifugal force field, which was reported by Nakamura et al. [27] to enable fluidizing fine particles which have high inter-particle cohesive forces. The system consists of a porous cylindrical gas distributor inside a plenum chamber, both axisymmetric, in which the former rotates inside the latter. This rotational motion forces the bed particles towards the porous wall by centrifugal force while the fluidizing gas flowing inwards balances this force. In a more recent design, Wilde and Broqueville [28] and Wilde [29] proposed a rotating fluidized bed but with tangential injection of fluidizing air via multiple gas inlet slots. While being successful in reducing particle entrainment, the authors reported channeling and slugging of the bed due to low bed loading. The system was further improved by Eliaers et al. [30] for drying of biomass.

3.4 Swirling fluidized beds

As the name implies, the swirling fluidized bed creates swirling motion of the bed, which is achieved either by injecting air using multiple tangential inlets at the bottom of the bed [31] or by using annular-blade type air distributors [32-35]. While the tangential injection of air creates swirling in the former, the inclined distributor blades create fluidization and swirling of the bed in the latter [33-35]. The bed is also known as the toroidal bed (Torbed®) owing to the toroidal motion of the particles superimposed on the swirling motion. Recently, the annular-blade distributor was successfully integrated with conical bed and developed as biomass combustors by [36-38]. Although the bed was conical, the authors designated their bed also as swirling fluidized bed.

The swirling fluidized bed is however limited only to shallow bed operations as the bed experiences rapid lateral momentum attenuation. Apart from this, the bed requires the use of a centre body to eliminate possible creation of a dead zone in the center of the bed. As a result, the effective bed area is an annular region. At higher operating velocities, due to the high centrifugal force, the bed is thrown outwards and some valuable amount of fluidizing gas bypasses the bed at the inner part of the annular region.

4 Conclusion

Several conclusions can be drawn from this review:

- a) Numerous distributors have been designed, developed and studied for utilization in specific applications of fluidized bed systems. The efforts were focused mainly on achieving good air distribution inside the bed without proportionate increase in pressure drop due to the distributor.
- b) Although similar, the vortexing, cyclonic, rotating and swirling fluidized bed have fundamental differences and unique hydrodynamics. The existence of these beds is proof of their advantage over conventional fluidized beds.
- c) Several important parameters of interest among researchers in characterizing the improvements of the fluidized bed system were U_{mf} , ΔP_d , ΔP_b and the regime of operation which are normally presented in the form of pressure-velocity curves.

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References

1. D. Kunii, O. Levenspiel, *Fluidization Engineering*, 2nd ed., Butterworth-Heinemann, (1991)
2. D. Geldart, J. Baeyens, The design of distributors for gas-fluidized beds, *Powder Technology*, **42**(1), pp. 67-78 (1985)
3. J.C. Agarwal, W.L. Davis, D.T. King, Fluidized-bed coal dryer, *Chem. Eng. Progr.* **58**(11), pp. 85-90 (1962)
4. R. Siegel, Effect of distributor plate-to-bed resistance ratio on onset of fluidized-bed channeling, *AIChE Journal*, **22**(3), pp. 590-592 (1976)
5. C.K. Gupta, D. Sathiyamoorthy, *Fluid Bed Technology in Materials Processing*, CRC Press, New York (1998)
6. A.S. Mujumdar, *Handbook of Industrial Drying*, 3rd ed., CRC Press: Boca Raton (2007)
7. M. Wormsbecker, T.S. Pugsley, H. Tanfara, The influence of distributor design on fluidized bed dryer hydrodynamics, 12th Int. Conf. on Fluidization, paper 100 (2007)
8. M. Wormsbecker, T.S. Pugsley, Distributor induced hydrodynamics in a conical fluidized bed dryer, *Drying Technology*, **27**(6), pp. 797-804 (2009)
9. S.Y. Son, D.H. Lee, G.Y. Han, D.J. Kim, S.J. Sim, S.D. Kim, Effect of air distributor on the fluidization characteristics in conical gas fluidized beds, *Korean Journal of Chemical Engineering*, **22**(2), pp. 315-320 (2005)
10. W. Ciesielczyk, Novel gas distributor for fluidized bed drying of biomass, *Drying Technology*, **27**(12), pp. 1309-1305 (2009)
11. D. Sathiyamoorthy, M. Horio, On the influence of aspect ratio and distributor in gas solid fluidized beds, *Chemical Engineering Journal*, **93**(2), pp. 151-161 (2003)
12. C. Sobrino, J.A. Almendros-Ibáñez, D. Santana, M. De Vega, Fluidization of Group B particles with a rotating distributor, *Powder Technology*, **181**(3), pp. 273-280 (2008)

13. C. Sobrino, N. Ellis, M. de Vega, Distributor effect near the bottom region of turbulent fluidized bed, *Powder Technology*, **189**(1), pp. 25-33 (2009)
14. S.M. Aworinde, D.J. Holland, J.F. Davidson, Investigation of a swirling flow nozzle for a fluidised bed gas distributor, *Chemical Engineering Science*, **132**, pp. 22-31 (2015)
15. C.E. Dodson, Torftech Limited, *Apparatus for processing matter in a turbulent mass of particulate material*, US Patent 4,479,920, (1984)
16. J. Shu, V.I. Lakshmanan, C.E. Dodson, Hydrodynamic study of a toroidal fluidized bed reactor, *Chemical Engineering and Processing*, **39**(6), pp. 499-506 (2000)
17. N.K. Sowards, Energy Products of Idaho, *Low pollution incineration of solid waste*, US Patent No. 4,060,041, (1977)
18. S. Nieh, G. Yang, Particle flow pattern in the freeboard of a vortexing fluidized bed, *Powder Technology*, **50**(2), pp. 121-131 (1987)
19. J. Zhang, S. Nieh, Swirling, reacting, turbulent gas-particle flow in a vortex combustor, *Powder Technology*, **112**(1), pp. 70-78 (2000)
20. C.S. Chyang, K.C. Lo, K.L. Wang, Performance evaluation of a pilot scale vortexing fluidized bed combustor, *Korean Journal of Chemical Engineering*, **22** (5), pp.774-782 (2005)
21. F. Duan, C.S. Chyang, S.H. Hsu, J. Tso, Combustion behavior and pollutant emissions of batch fluidized bed combustion, *Journal of the Taiwan Institute of Chemical Engineers*, **44**(6), pp. 1034-1038 (2013)
22. F. Duan, C. Chyang, Y. Chin, J.Tso, Pollutant emission characteristics of rice husk combustion in a vortexing fluidized bed incinerator, *Journal of Environmental Sciences*, **25**(2), pp. 335-339 (2013)
23. R. Kaewklum, V.I. Kuprianov, Experimental studies on a novel swirling fluidized-bed combustor using an annular spiral air distributor, *Fuel*, **89**(1), pp. 43-52 (2010)
24. T. Madhiyanon, N. Piriyaungroj, S. Soponronnarit, Cold flow behaviour study in novel cyclonic fluidized bed combustor (Ψ -FBC), *Energy Conversion and Management*, **49**(5), pp. 1202–1210 (2008)
25. T. Madhiyanon, A. Lapirottanakun, P. Sathiruangsak, S. Soponronnarit, A novel cyclonic fluidized bed combustor (Ψ -FBC): Combustion and thermal efficiency, temperature distributions, combustion intensity and emission of pollutants, *Combustion and Flame*, **146**(1), pp. 232-245 (2006)
26. T. Madhiyanon, P. Sathiruangsak, S. Soponronnarit, Co-combustion of rice husk with coal in a cyclonic fluidized-bed combustor (Ψ -FBC), *Fuel*, **88**(1), pp. 132-138 (2009)
27. H. Nakamura, T. Tokuda, T. Iwasaki, S. Watano, Numerical analysis of particle mixing in a rotating fluidized bed, *Chemical Eng. Science*, **62**(11), pp. 3043-3056 (2007)
28. J. De Wilde, A. de Broqueville, Experimental investigation of a rotating fluidized bed in a static geometry, *Powder Technology*, **183**(3), pp. 426-435 (2008)
29. J. De Wilde, Gas–solid fluidized beds in vortex chambers, *Chemical Engineering and Processing: Process Intensification*, **85**, pp. 256-290 (2014)
30. P. Eliaers, J.R. Pati, S. Dutta, J. De Wilde, Modeling and simulation of biomass drying in vortex chambers, *Chemical Engineering Science*, **123**, pp.648-664 (2015)
31. S.H. Kumar, D.V.R. Murthy, Minimum superficial fluid velocity in a gas–solid swirled fluidized bed, *Chemical Engineering and Processing: Process Intensification*, **49**(10), pp. 1095-1100 (2010)

32. F. Ouyang, O. Levenspiel, Spiral distributor for fluidized beds, *Industrial & Engineering Chemistry Process Design and Development*, **25(2)**, pp. 504-507 (1986)
33. M.F. Mohideen, S. Md Seri, V. Kumar, V.R. and Raghavan, Experimental studies on a swirling fluidized bed with annular distributor, *Journal of Applied Sciences*, **Vol. 11, No. 11**, pp. 1980-1986 (2011)
34. M.F. Mohideen, S.M. Seri, V.R. Raghavan, Fluidization of Geldart Type-D Particles in a Swirling Fluidized Bed, In *Applied Mechanics and Materials*, **Vol. 110**, pp. 3720-3727, Trans Tech Publications (2012)
35. M.F. Mohideen, M.F., S.A. Sulaiman, V.R. Raghavan, Hydrodynamics of oil palm frond in a swirling fluidized bed dryer, In *Applied Mechanics and Materials*, **Vol. 117**, pp. 1829-1833, Trans Tech Publications (2012)
36. V.I. Kuprianov, R. Kaewklum, K. Sirisomboon, P. Arromdee, S. Chakritthakul, Combustion and emission characteristics of a swirling fluidized-bed combustor burning moisturized rice husk, *Applied Energy*, **87(9)**, pp. 2899-2906 (2010)
37. P. Arromdee, V.I. Kuprianov, A comparative study on combustion of sunflower shells in bubbling and swirling fluidized-bed combustors with a cone-shaped bed, *Chemical Engineering and Processing: Process Intensification*, **62**, pp. 26-38 (2012)
38. V.I. Kuprianov, R. Kaewklum, S. Chakritthakul, Effects of operating conditions and fuel properties on emission performance and combustion efficiency of a swirling fluidized-bed combustor fired with a biomass fuel, *Energy*, **36(4)**, pp.2038-2048 (2011)